INTERDISCIPLINARY STUDY OF WARM CORE RING PHYSICS, CHEMISTRY, AND BIOLOGY

PRINCIPAL INVESTIGATORS

Executive Committee

Chairman: Dana Kester, U.R.I.
Vice-Chairman: Peter Wiebe, W.H.O.I.
Glenn Flierl, M.I.T.
Terrence Joyce, W.H.O.I.
James McCarthy, HARVARD
David Schink, TAMU

Richard Backus, W.H.O.I.
James Bishop, LDGO
Patricia Blackwelder, NOVA
Otis Brown, MIAMI
Timothy Cowles, W.H.O.I.
Robert Evans, MIAMI
Greta Fryxell, TAMU
Gary Hitchcock, U.R.I.
Kevin Leaman, MIAMI
David Nelson, O.S.U.
Donald Olson, MIAMI
Thomas Osborn, U.B.C.
Michael Roman, MIAMI
Theodore Smayda, U.R.I.
Raymond Smith, S.I.O.
Joseph Wroblewski, DAL
Charles Yentsch, BIGELOW

CONTENTS

INTERDISCIPLINARY STUDY OF WARM CORE RING PHYSICS, CHEMISTRY AND BIOLOGY

Summary

We are conducting an interdisciplinary study of the structure and dynamics of Gulf Stream Warm Core Rings by a time series investigation of selected rings. This program consists of highly integrated components which include physical, chemical, and biological investigations and modeling studies. These components are designed to provide information on the structure of rings and exchange mechanisms at ring boundaries, on their marine chemistry, and on the environmental controls of biological activity of selected constituents associated with Warm Core Rings. This research is being conducted by approximately two dozen investigators from thirteen marine institutions. An interdisciplinary program of the scope proposed is required in order to understand the interdependence among biological, chemical, and physical processes in the ocean. This study of the structure and evolution of Warm Core Rings will enhance the understanding of fundamental oceanic processes and the role of rings in the region where they occur.

1. Introduction

Warm Core Rings form in the Slope Water region between the North American continental shelf and the Gulf Stream. These rings are bodies of water 100-200 km in diameter which result when a meander separates from the Gulf Stream. The Warm Core Ring (WCR) is comprised of a central core, the initial physical, chemical, and biological properties of which originate in the Sargasso Sea. This core is surrounded by a clockwise rotating remnant of the Gulf Stream, with surface speeds on the order of 50 to 100 cm/sec which we will refer to as the high velocity region. Between the high velocity region and the core is a transition region which corresponds to the somewhat indistinct southern boundary of the Gulf Stream. Outward from the high velocity region is a sharp boundary between the warm Gulf Stream remnant and the cold Slope Water; this continuous circular frontal zone corresponds to the "cold wall" of the Gulf Stream. Warm Core Rings do not immediately dissipate in the Slope Water region. They maintain their identity for a substantial period of time, slowly changing in character as they age.

Knowledge about WCRs has increased in the past several years because they are readily identifiable in satellite infrared images. Using combined satellite and ship of opportunity data Experimental Ocean Frontal Analysis Charts of the Gulf Stream/Slope Water region have been produced weekly by the Naval Oceanographic Office. These and other data have been used, by Bisagni (1976), Halliwell and Mooers (1979), Mizenko and Chamberlin (1979) for example, to characterize the frequency of occurrence and distribution of Warm Core Rings. Although some annual and interannual variability in WCR population is becomming evident, one can typically find

2-3 WCRs in the Slope Water at any given time having mean lifetimes of six months. Between the time of formation and absorption by the Gulf Stream these rings tend to migrate at a rate of three to five km/day in a southwesterly direction constrained by the Gulf Stream to the south and east and the continental shelf to the north and west. These general features of WCRs are illustrated in Figure 1.

During its lifetime a WCR is a site for a variety of oceanographic processes. It physically interacts with its surroundings by entraining Shelf, Slope, and Gulf Stream Water as can be detected in the satellite sea surface temperature distributions. During fall and winter, heat loss to the atmosphere produces thermal convection to greater depths within a WCR than in the surrounding Slope Water. Initially the core of a ring will contain warm water fauna and flora of the Sargasso Sea. These populations undergo a transformation as a result of the changing physical and chemical environment of a ring as well as due to invasion of organisms of Slope Water origin.

While little information is presently available on the physics, chemistry, and biology of Warm Core Rings, much has been learned in recent years from the study of cyclonic Cold Core Rings spawned by and found south of the Gulf Stream. The major observational results of this study are that: after formation individual rings carry with them a trapped volume of Slope Water in the upper portions of their central cores, they can be successfully tracked by remote means, they suffer a loss of potential and kinetic energy with a time scale of one year and undergo alterations in the chemical and biological states which cannot solely be linked to physical changes. Theoretically rings may be a highly stable form of nonlinear wave disturbance which moves through the surrounding fluid. Biological and physical modeling of the population density of particular organisms suggests that the decrease in population is dominated by biological processes.

These results of the Cold Core Ring program are important and provocative. They raise a number of questions concerning the processes which are important in determining the physical, chemical, and biological changes in rings. Is the energy decay due to vertical friction, lateral diffusion, air-sea interaction, effects of Rossby wave radiation, instabilities, etc.? What specific effects do changing temperatures, nutrients, light levels, heavy metals, etc. have upon the biological populations, and the cycling of elemental material? Answering these questions requires more specific data. Many of the processes active in cold and warm rings are unlikely to be fundamentally different from those elsewhere in the open ocean. However, a ring is a distinct hydrographic regime small enough to permit comprehensive analysis of physical, chemical, and biological structure yet large enough to provide a central core region where vertical processes are likely to dominate and a frontal boundary across which lateral transfers should prevail. It follows, therefore, that an interdisciplinary study of a ring should be able to relate these spatially dependent processes to the observed changes of the ring.

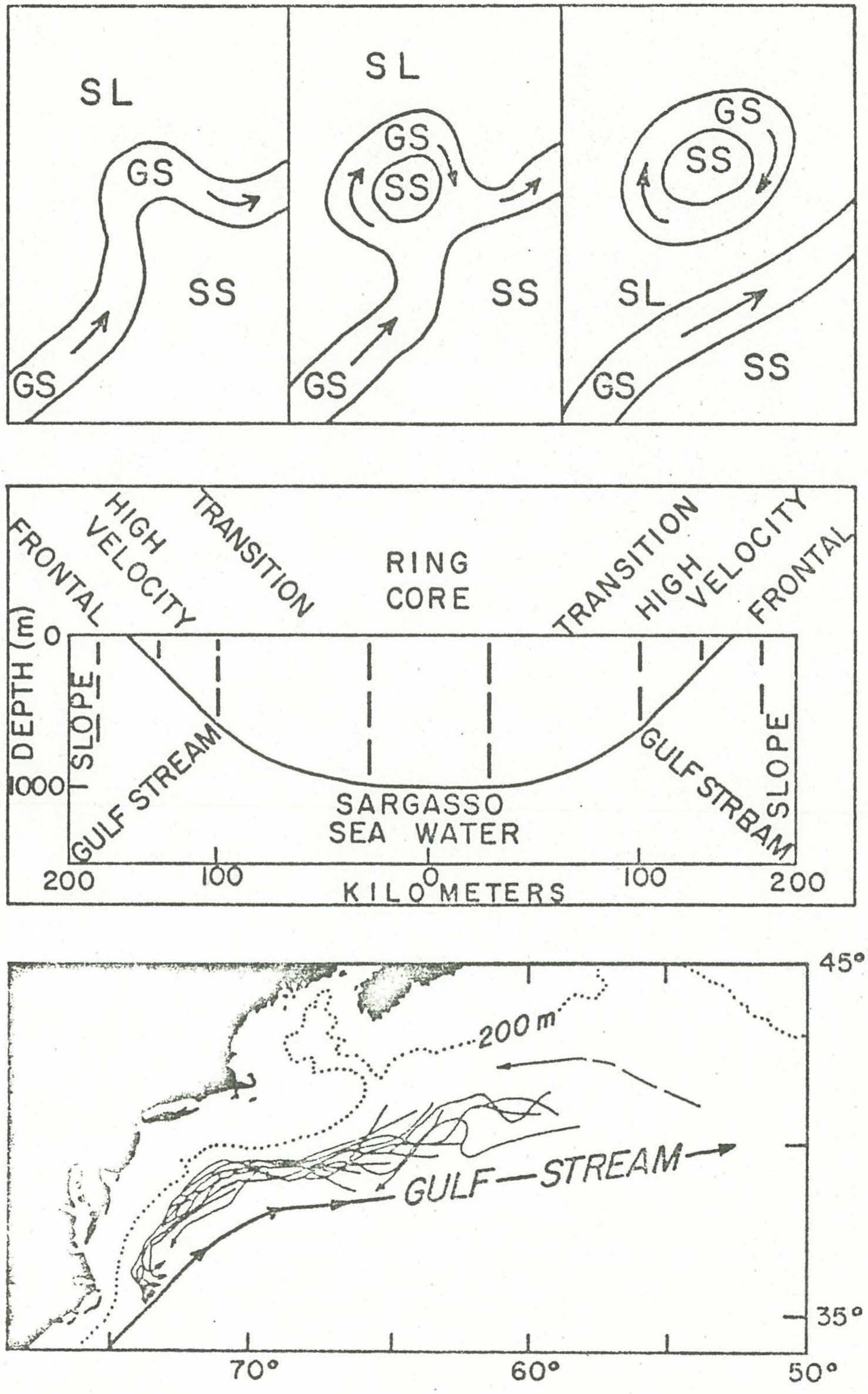


Figure 1. Upper: Three stages in the formation of a Warm Core Ring from a Gulf Stream Meander: SL = Slope Water; GS = Gulf Stream Water; SS = Sargasso Sea Water. Middle: Vertical cross-section of a Warm Core Ring. Lower: Tracks of Warm Core Rings in the Slope Water (Lai and Richardson, 1977).

The results of previous studies have shown the need for a well-coordinated study to understand the physical, chemical and biological processes occurring in rings. They are easily tracked by satellite infrared techniques and are readily accessible. In addition, Warm Core Rings are themselves intrinsically interesting. They are subjected to strong wintertime convective cooling and represent large perturbations in sea surface temperature and oceanic-atmospheric heat exchange. In addition to playing an important role in the heat budget of this region, Warm Core Rings are probably strong contributors to the momentum balance of the Slope Water circulation as well. Warm Core Rings may also have a significant influence on the Shelf Water circulation: Smith (1978) estimated that episodic collisions of Warm Core Rings with the shelf/slope front could transport up to 30% of the annual air/sea flux of heat and salt into the continental shelf water off Nova Scotia.

In many regards the region impacted by Warm Core Rings is of great economic importance. Rings are an important factor in the functioning of our offshore fisheries. One active site for deep ocean waste disposal is frequently occupied by Warm Core Rings and the distribution of pollutants from this site and also from any spills in the offshore oil regions could be dominated by Warm Core Ring advection.

This study is timely because we can apply the information gained in the Cold Core Ring program, explore the capabilities of remote sensing in a system with large variations in sea surface temperature, elevation, wave state and ocean color. There are also strong imperatives for understanding the physics, chemistry, and biology of Warm Core Rings which will be discussed in the following section.

2. Program Objective

We are studying the 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.

This general program objective is being advanced by considering the following specific questions.

a. What is the physical structure and motion of a ring and how does it change as the ring ages? What are the physical processes responsible for ring/Slope Water iteraction and ring decay?

b. How do rings affect the large-scale chemical transport in the Slope Water region? Do rings enhance vertical fluxes in their vicinity and thus accelerate biological and chemical processes?

c. How are the distributions of phytoplankton, zooplankton and nekton related to environmental factors within a ring? What controls the primary production and the activity at higher trophic levels within a ring?

The answers to these questions will be obtained, the program objective achieved, only by a carefully coordinated program employing a wide variety of specialists in physics, chemistry, and biology.

Physical Aspects

Major questions being addressed by physical studies are:

i. What is the physical structure, motion, and dynamics of a ring?

ii. What are the mechanisms of exchange and fluxes of properties at the ring boundaries?

Rings represent one of the most intense forms of mesoscale activity. They appear to exist and persist as relatively isolated phenomena, but it is important to understand the extent to which this description is dynamically corret. It is not clear whether rings are merely large tracer particles imbedded in the Slope Water circulation or if they move relative to their surroundings. Theoretical models provide one approach to this question but they require a detailed description of the current and density fields as an initial condition. It is already known that rings are not radially symmetric. The determination of ring structure will permit construction of models to be used for short time prediction of ring position and as bases for studying the physical effects of changing external conditions and exchanges across ring boundaries.

It is by these exchanges that rings interact with and leave an imprint upon their environment. The ring is a captive front and lateral exchanges due to intrusive motions can be expected to be intense on the outer boundaries. The frontal zone represents a boundary in various physical, chemical, and biological properties each of which to varying degrees provides a water mass tracer. Heat, salt, oxygen, nutrients, and possibly biological populations can be expected to be exchanged laterally at these boundaries. Estimates of heat and salt fluxes can be made in a straightforward manner but other quantities will need to be estimated indirectly. At the ring center vertical processes should be dominant with turbulent mixing at the base of the mixed layer playing an important role in the nutrient cycling. Wintertime air-sea interactions at the ring core can penetrate to greater depth than in the surrounding Slope Water because of the ring's anomalous heat content and deeper permanent pycnocline. Vertical friction can cause decay of kinetic energy as well as bring about property exchange by driving secondary circulations within a ring. The near surface inflow and deeper outflow suspected in Cold Core Rings could be due to internal friction.

It is our intention to relate changes in the physical structure of the ring to dynamics important on ring and sub-ring scales.

Chemical Aspects

There are four questions related to the chemical study required to meet the objectives of the Warm Core Ring program:

i. What is the large-scale chemical transport by rings?

ii. What is the vertical flux of chemical constituents within rings?

iii. How do the distributions and cycling of nutrients and trace metals relate to biological processes?

iv. What is the chemical resolution of physical processes of mixing, entrainment, and advection?

The upper 500 m of Slope Water is higher in nutrients and lower in oxygen than upper waters of the Sargasso Sea. Sharp chemical gradients occur across the Gulf Stream frontal region. When a Warm Core Ring, with its core of Sargasso Sea Water, is injected into the Slope Water region, the subsequent exchange of waters results in large-scale chemical transfers. Eventually the ring is absorbed by the Gulf Stream and nutrients are lost from the Slope Water. Chemical transport also occurs as a result of the input and partial confinement of chemicals in Warm Core Rings during their advection through the region. Deposition from air masses that have passed over the eastern United States, discharge of industrial wastes at Deep Water Dumpsite 106, and the release of petroleum hydrocarbons during transportation or offshore drilling represent three modes of chemical input to Warm Core Rings from anthropogenic sources. Chemical transport by rings is an essential element in defining their interaction with waters in the Slope Water and their role in the fate of pollutants. The oxygen and nutrient data will be particularly useful in providing boundary conditions for the modeling of ecological and physical processes associated with Warm Core Rings.

Warm Core Rings contrast most sharply with their surroundings in the upper 1000 m; but the upper waters are coupled to the waters below by vertical fluxes of material. The nature of this coupling is one of the most ineresting problems in chemical oceanography and an area where great progress is now being made. The sharp lateral contrasts provide an excellent opportunity to examine the effects of oligotrophic waters (within the rings) upon the transport of material to the deep ocean. Three mechanisms contribute to the vertical flux: i) particulate settling, ii) active biological transport through vertical migration, and iii) physical mixing and advection. Furthermore, the ring boundary processes probably enhance both horizontal and vertical transport as compared to more simply stratified systems.

In addition to the nutrients there is evidence that other constituents such as trace metals may effect biological activity. Recent studies have also shown oceanographic consistency between trace metal distributions and nutrient or hydrographic variations in the ocean. The chemical contrasts across Warm Core Rings and the multidisciplinary scope of this program including physics and biology in addition to chemistry provide an exceptional opportunity to gain further understanding of processes which affect trace metal distributions and the effect of these metals on biological processes. The time-series approach of this investigation will be especially valuable in the investigations of trace metal chemistry.

Chemical gradients associated with Gulf Stream Ring systems may help resolve mixing processes and advective entrainment. continuous profiles of oxygen have proven to be useful in distinguishing Gulf Stream, Slope, and Sargasso Sea Waters in Cold Core Rings. In addition, the small-scale variability provides an indication of lateral interleaving of waters in frontal zones. Silicate distributions provide a useful index for deep water origins in the northwest Atlantic. Radium-228 tags water from the near-shore regions. Dozens of Ra-228 profiles will be taken in order to delineate lateral and vertical mixing of waters in the uppermost 500 m of the ring and to help define mixing processes in the bottom 500 meters of the water column. Profiles of surplus radon also serve as a valuable tracer of near-bottom exchanges and will be used extensively to examine the nature of ring-sea floor interactions. In the upper 100 m of water, profiles of radon deficit can help to determine vertical (and perhaps horizontal) mixing processes, and in particular will be used to evaluate vertical exchange rates.

Biological Aspects

The biological investigations in the Warm Core Ring program are focused on two questions:

i. To what degree do physical and chemical parameters determine the distribution and abundance of oceanic biota in an easily tracked parcel of water?

ii. What is the importance of vertical processes in regulating cycling of major nutrients and trophic structure in pelagic waters?

Rings provide an excellent setting for addressing these questions because of their semi-enclosed nature and because of the high contrast between ring core and surrounding waters. Based on the study of Cold Core Rings one can expect to observe time-related changes in the horizontal and vertical distributions, migration patterns, reproduction cycles, biochemical composition and physiology of the organisms. Within a ring, horizontal and vertical gradients in features such as nutrients are associated with flow-field dynamics. We expect plankton communities to vary along such gradients within the ring mesocosm since biotic structure is related to environmental factors. At the level of phytoplakton community organization, this may be evident in cell size distribution. Rate of primary production, nutrient uptake, sinking, and zooplankton grazing are affected by phytoplankton cell size. Thus the dynamics of populations of different cell sizes represent a major problem area relevant to both the Warm Core Ring experiment and biological oceanography in general. Horizontal advective losses in the ring central core are minimized and we expect that entrained, identifiable populations growing under natural conditions can be followed over suitable periods.

Intensive study of vertical fluxes of elemental material and *in situ* recycling within a Warm Core Ring are required to understand these processes in a ring system and to extend this understanding to the study of zooplankton/phytoplankton/nutrient/trace metal interactions elsewhere in the ocean. The advective and diffusive supply rates of nitrogen, silicon and phosphorus to the euphotic zone are generally considered to be among the fundamental factors limiting primary production and the distribution of phytoplankton species. However, in the open ocean these supply rates can be only crudely estimated. Thus, the response of oceanic phytoplankton to known rates of nutrient enrichment has not been satisfactorily determined. A Warm Core Ring may be uniquely suitable for this purpose because it is a physically discrete body of water in which these processes can be studied as it undergoes physical, chemical, and biological transformations with time.

Zooplankton grazing studies with selected species, in conjunction with fine-scale vertical distribution data, can provide direct assessment of grazing pressure on particulate material, as well as estimates of overall carbon utilization by zooplankton herbivores. Shipboard grazing studies can assess the feeding response of zooplankton herbivores under more controlled conditions in order to examine feeding differences between species and various developmental stages.

Warm Core Rings as distinct hydrographic entities are responsible for creating and maintaining much of the mesoscale heterogeneous distribution of phytoplakton, zooplankton, ichthyoplankton and nekton in the Slope Water and over the shelf. They are an important, but relatively unknown factor affecting the living resources of the region. Studies of the spatial distribution of the plankton can contribute significantly to our understanding of this aspect of ring influence. Such studies should focus on the gradients in population structure or community composition within and adjacent to the ring, the relationship between species dispersal and physical features which indicate intrusion of warmer (or cooler and less saline) water in ring exchange processes, and the temporal and spatial variability in abundance associated with the different ring hydrographic regimes. We expect to observe significant alteration of the physiological states of organisms transported into warmer water from the Slope Water and shelf and into cooler less saline water from the ring core.

3. Overview of Program Components

There are five main scientific components in this interdisciplinary investigtion of Warm Core Rings. They are:

a. Experimental and descriptive physical oceanography.

b. Chemical distributions and processes.

c. Biological spatial patterns.

d. Plankton physiology.

e. Analytical and numerical modeling.

Corresponding areas of research have been structured in a complementary fashion to carry out the tasks described in Section 2 and to provide the information required to understand oceanic processes related to Warm Core Rings. Table 1 lists the investigators associated with this program under the primary component of work with which they are associated. It must be recognized, however, that some aspects of their work contribute to more than one component.

a. Experimental and Descriptive Physical Oceanography

Sea surface infrared temperature (SST) images will provide a continuous, synoptic description of Warm Core Ring presence, distribution, and horizontal structure. This information will be available and analyzed at weekly intervals during the program and daily during periods of active field work.

For each field operation a particular ring either selected initially or during a previous cruise will be remotely tracked using SST. The first shipboard activity will be to map the ring using XBTs and a hull-mounted doppler current profiler. Then CTD-O_2 sections through the ring will be made which together with the near surface current field should define the fields of heat, salt, oxygen, mass, and momentum of the ring. Loran-C tracked drifters with temperature sensors (or a cyclosonde) and particle interceptor traps will be deployed at specific regimes of the ring. These drifters will serve as sites for small-scale experiments in both the ring center and the frontal zone. Vertical profiles of turbulent energy dissipation will be obtained to understand mixing processes in these regions.

b. Chemical Distributions and Processes

Horizontal and vertical distributions of oxygen, nitrate, nitrite, phosphorus, and silicate will be determined for use in defining chemical, biological, and physical processes in the rings. The distribution and principal chemical forms of specific trace metals (Fe, Cu, Cd, and Hg)

Table 1. Principal Investigators and their primary areas of research in the Warm Core Rings Program

INVESTIGATOR	INSTITUTION	AREA OF WORK
1. Experimental and Descriptive Physical Oceanography		
Terrence Joyce	Woods Hole Oceanographic Institution	CTD-O_2 and Current Profiler Studies
Kevin Leaman & Robert Evans	University of Miami	Cyclesonde and Drifter Measurements
Don Olson & Otis Brown	University of Miami	Remote Sensing Sea Surface Temperature
Thomas Osborn	University of British Columbia	Turbulent Energy Dissipation
2. Chemical Distributions and Processes		
James Bishop	Lamont-Doherty, Columbia University	Particulate Flux of Chemicals
Dana Kester	University of Rhode Island	Nutrient Studies
David Schink	Texas A&M University	Radium-radon Studies
3. Biological Investigations		
A. Spatial Patterns		
Richard Backus	Woods Hole Oceanographic Institution	Mid-Water Fish Distributions
*Patricia Blackwelder	Nova University	Coccolithophore Abundance and Morpholoty
G. Fryxell	Texas A&M University	Phytoplankton Species Composition
Peter Wiebe	Woods Hole Oceanographic Institution	Macrozooplankton Distribution
Charles Yentsch & Raymond C. Smith	Bigelow Laboratory, Maine S.I.O.	Remote Sensing of Biologically Important Parameters
B. Plankton Physiology		
Timothy Cowles	Woods Hole Oceanographic Institution	Macrozooplankton Grazing and Egg Production
James McCarthy	Harvard	Nitrogen Nutrient Dynamics
David Nelson	Oregon State University	Silicon Nutrient Dynamics
Michael Roman	University of Miami	Microzooplankton Grazing Studies
Theodore Smayda & Gary Hitchcock	University of Rhode Island	Phytoplankton Growth Studies
4. Analytical and Numerical Modeling		
Glenn Flierl	MIT	Circulation and Transport Modeling
Joseph Wroblewski	Dalhousie University	Biological Modeling

*NSF Funding Pending

will be investigated in order to determine the relationship between these metals and biological processes and to further understand the marine geochemistry of these constituents.

Fluxes of chemical constituents in the upper waters, near the sea floor, between the ring and surrounding waters, and vertically within the ring will be assessed by observing and tracing the distributions of radon, radium-228, selected metals, and particulate matter. These studies will contribute to the estimation of exchange rates across ring boundaries. Analyses of material from large volume pumping and particle interceptor traps will permit quantitative and qualitative characterization of passive particle fluxes.

Biological Investigations

The goal of understanding the biological changes that occur as a ring ages requires that investigtors with varied areas of expertise work together. While the biological portion of the program is divided into two parts to emphasize the two separate approaches of the research (i.e., one dependent upon intensive temporal and spatial sampling and the other utilizing shipboard experimentation), these efforts are mutually inderdependent. The information developed by one group is required by the other for optimal interpretation of their respective data.

The combined biological effort reflects the most tractable problems which can be investigated within the context of the Warm Core Rings program. There is no question that the microbes and gelatinous zooplankton may be as important as any of the groups of organisms targeted for study, but investigations working with these groups of organisms find it difficult to generate rate per unit volume sea water values for the activity of the biota comparable to those for phytoplankton and more easily captured crustacea. Future incorporation of research representing these areas, in addition to that of fish physiology, should be considered for support if good proposals are received.

c. Biological Spatial Patterns

An intensive temporal and spatial sampling effort is needed to examine the changes in Warm Core Ring biota with time, the interaction between communities of different origins in the ring transition regions, and the impact of rings on the Slope and Shelf Water biota. In order to obtain cross-sections of species distribution, abundance and variability at specific locations, repeated sampling of the ring core and the transition areas will be done using opening/closing midwater trawls and water bottles. Component projects will focus on the midwater fishes (myctophids, gonostomatids, and sternoptychids) and the zooplankton (euphausiids, molluscs, and copepods), the biomass of both the macrozooplankton and that portion of the microzooplankton collected by 64 m net, the phytoplankton biomass (as chlorophyll), and the phytoplankton species distribution and abundance.

d. Plankton Physiology

Initial differences between ring and surrounding waters which diminish with time will permit investigators to follow the evolution of processes such as silicon and nitrogen cycling in a parcel of water which can be followed with certainty over time. The composition of the herbivore population and feeding potential will change as physical parameters (e.g., water temperature) and biological features (e.g., predation pressure, phytoplankton cell size and quality) change with ring decay. Numerous aspects of zooplankton physiology (e.g., ingestion, respiration, egg production, and growth) will be monitored for certain dominant copepods and possibly euphausiids. If other zooplankton groups become numerically important, attempts will be made to study these too. Measurements of zooplankton (including some microzooplankton) processes will be made both in situ and in shipboard incubators using natural particulate material.

State of the art isotopic techniques will be employed to determine the rates of silicon, nitrogen, phosphorous, and carbon incorporation by phytoplankton. The nutritional sufficiency of the environment will be assessed. Studies of elemental cycling will permit us to characterize the nutrient fluxes within the ring, across the thermocline at the ring center, and to a lesser degree across the ring-Slope Water interface.

e. Analytical and Numerical Modeling

Modeling of physical, chemical, and biological aspects of the ring system provides one important focus for this program: models, both conceptual and mathematical, represent precise statements of hypotheses and require synthesis of many observations in their testing. Currently there exist several models for the structure of eddies which propagate without change in form (except for frictional decay). We will investigate whether the data are consistent with such models. If consistent, then the stability of such solutions and the effects of changes in the exterior flow upon ring structure must be examined. If the data do not seem to agree with solitary wave models, short-term evolution of ring-like features will be examined. Numerical and observational particle trajectories in a Warm Core Ring will also be examined and compared in order to investigate which regions of the ring are "trapped."

Other modeling efforts will focus on numerical simulation studies of physical, chemical, and biological processes occurring within the rings. The goal is to build a comprehensive yet practical model which considers most of the relevant processes which govern the mesoscale distribution of nonconservative variables (chlorophyll, nutrients, radionuclides, etc.), along with smaller perhaps nonspatial models which elucidate the biological and chemical mechanisms of particular interest. Modeling will examine the relative roles of physical and biological processes in causing population changes of single zooplankton species. This will be particularly useful for animals which live for several months and do not reproduce continuously throughout the lifetime of a ring.

4. Sampling Strategy

A range of time scales can be identified in considering the physical, biological, and chemical processes associated with WCRs. Diel variations are important for some biological processes such as vertical migration and photosynthesis. Events on the time scale of days are typical for the rotation of waters around the core, for the generation time of phytoplankton species, and for local mixing at frontal boundaries. A time scale of weeks is significant for transformations in the overall characteristics of a ring and seasonal differences between the warm and cold periods of the year are evident. The field program has been designed to provide information from diel to several month scales.

Spatially, too, scales from centimeters to hundreds of kilometers must also be considered. Turbulent dissipation, tracer mixing and species interactions occur on centimeter or smaller scales. Plankton patchiness and water mass intrusions generate variability on the meter to kilometer scales. The front separating the core from the Slope Water is characterized by 10 km scales while the ring itself is of order 100 km. Finally, by the fluxes of heat, vorticity, tracers, nutrients, and biota, the ring affects a strip of Slope Water several hundred kilometers wide.

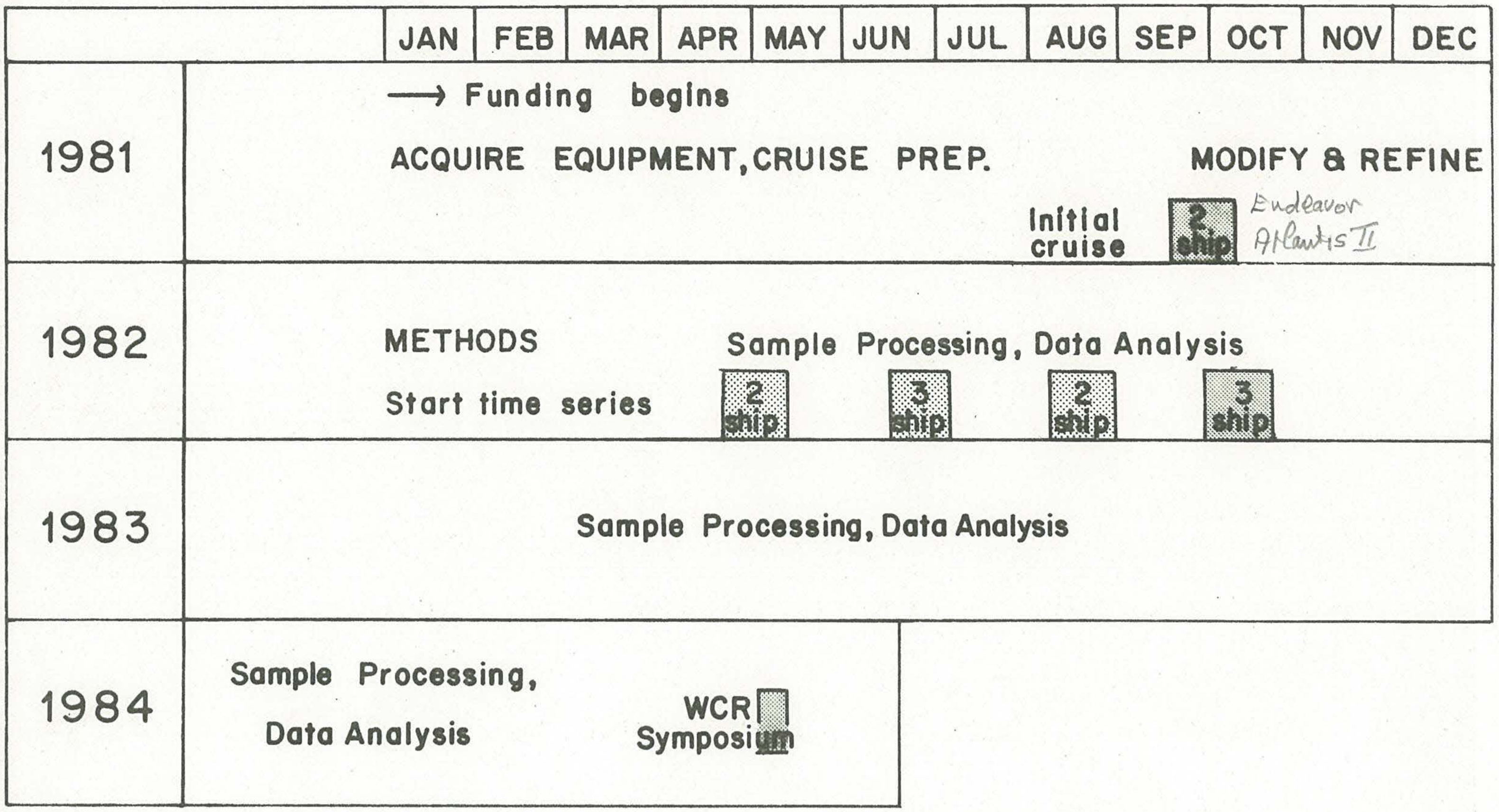
A time series experiments will occur during the stratified period of the year (1982). This experiment consists of a series of two and one-half week cruises separated by five to six week intervals. The series will span a significant portion of the life of a ring. Observations will be made within the duration of the cruise to obtain information on weekly time scales and the work on the stations will be made for diel comparisons where necessary. Closely-spaced stations will be occupied in the frontal regions, with sparser sampling over the whole area of the ring. Vertical profiling will cover scales ranging from centimeters to the full ocean depth.

The research in this program covers a three and a half year period beginning January 1981 and is shown in Figure 2. There are two periods of field activity consisting of:

1) A first cruise in September 1981 to obtain initial data on a Warm Core Ring, test experimental techniques, and provide an opportunity to integrate the activities of the principal investigators prior to the multi-ship program which follow.

2) A summer-time series of four multi-ship cruises designed to follow a single ring through most of its life cycle with a high probability of obtaining a series of "snapshots" of the physical, chemical, and biological state of a ring.

In the future, we will consider a winter time-series to contrast with the summer study and to examine the vertical mixing processes due to convective overwintering.



WCR General Meetings: March' 81, January '82, August '83

Data Workshops: January '82, March '83

Figure 2. Three and one half year time diagram showing major milestones in the Warm Core Ring Program.

a. Temporal Sampling

The Warm Core Ring census work of Chamberlin and co-workers for the period 1976-1978 has been summarized in Table 2. Using a mix of remote sensing and ship-of-opportunity SST data the positions of ring center at mid-month have been shown for eight different regions of the Slope Water. Within each year the rings are identified alphabeticallly and lines have been drawn which aid in following individual rings. This data base, though short, has aided us in our scheme for temporal sampling.

To the west of New England Seamounts, which lie in region 3, young rings found in region 4 tend to persist for 4-5 months drifting into regions 7 and 8 before being absorbed by the Gulf Stream. The 1982 time series begins in May and ends in October. In Slope Water region 4 there is a good chance that a ring can be found in May which will persist to September. If one can be found in region 4 this will be the one selected for our summertime series. This ring can then be followed as it drifts southwest with the final October cruise likely to catch it strongly interacting with the Gulf Stream off Cape Hatteras.

This strategy provides the greatest probability of meeting the time-series objectives of this program. In the event that not all cruises in each series can be conducted in a single ring, it will be possible to supplement more limited time series with information from two or more rings. While the time-series nature of this program has been emphasized in designing the field program, it is evident that many of the components can meet their objectives and provide substantial scientific knowledge even if a complete time series cannot be obtained due to a premature absorption of the ring by the Gulf Stream.

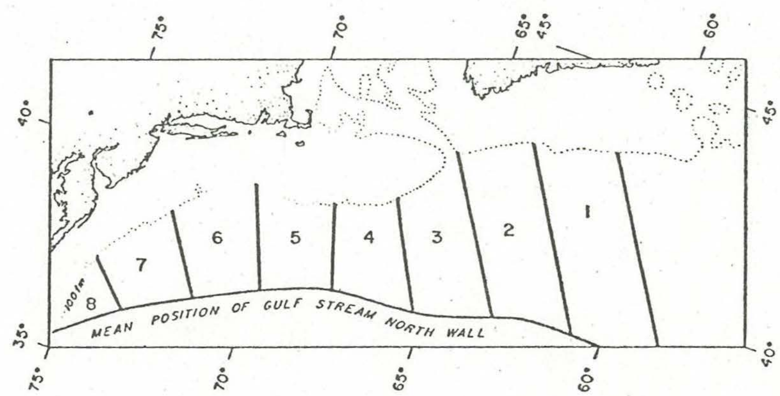
b. Spatial Sampling

The ship-related field investigations on each of the Warm Core Ring cruises in Figure 2 are of two basic types. Some of the studies require near-synoptic measurements over a region comparable to the size of a ring while others require intensive measurements over moderate periods of time as selected locations relative to a ring. Because of these diverse requirements, several ships are needed. To fully accommodate each investigator's complete program, three ships are necessary. However, certain experiments will not be carried out on every cruise and manpower limitations compel restricting the total scope of the sampling program. We therefore have alternated three ship operations with two ship operations during the summer time-series. Schematic diagrams of station positions and cruise tracks for each of the ships are shown for a two-ship operation (Figure 3) and a three-ship operation (Figure 4). For purposes of illustration we have used the conditions for the 1 November, 1978 Experimental Ocean Frontal Analysis Chart.

Ship 1 will accommodate 16 scientists and have a speed capability of 12-14 knots to provide rapid coverage of ring features using a star-shaped

Table 2. Three-year summary of WCR activity in the Slope Water. Within a given year, rings are ordered alphabetically. Code for eight regions is shown below table.

Year	Month	1	2	3	4	5	6	7	8	Month
1976	J			75I				75E		J
	F				75I			75E		F
	M			76A	75I			75E		M
	A					76B				A
	M				76C	76B				M
	J		76E	76D	76C		76B			J
	J		76E		76D	76C				J
	A				76D		76C			A
	S				76D			76C		S
	O		76F			76D			76C	O
	N		76F		76G	76D				N
	D			76F	76G		76D			D
1977	J		77A	76F	76G		76D			J
	F	77B		77A		76G				F
	M		77C		77A		76G			M
	A	77D	77C	77E		77A		76G		A
	M	77D,F	77C	77G	77E	77A	77H		76G	M
	J	77D			77E	77A		77H		J
	J	77D				77E	77A	77H		J
	A		77D		77I		77E	77A	77H	A
	S		77D			77I	77E	77A		S
	O			77D		77I				O
	N				77D		77I			N
	D					77D	77I			D
1978	J						77D	77I		J
	F						77D	77I		F
	M									M
	A			78B	78A					A
	M		78C	78B	78A					M
	J	78F	78E	78D		78A				J
	J		78F	78E	78D	78A				J
	A	78G	78F	78E		78D	78A			A
	S					78D		78A		S
	O				78H		78D		78A	O
	N				78H		78D			N
	D	78I						78D		D



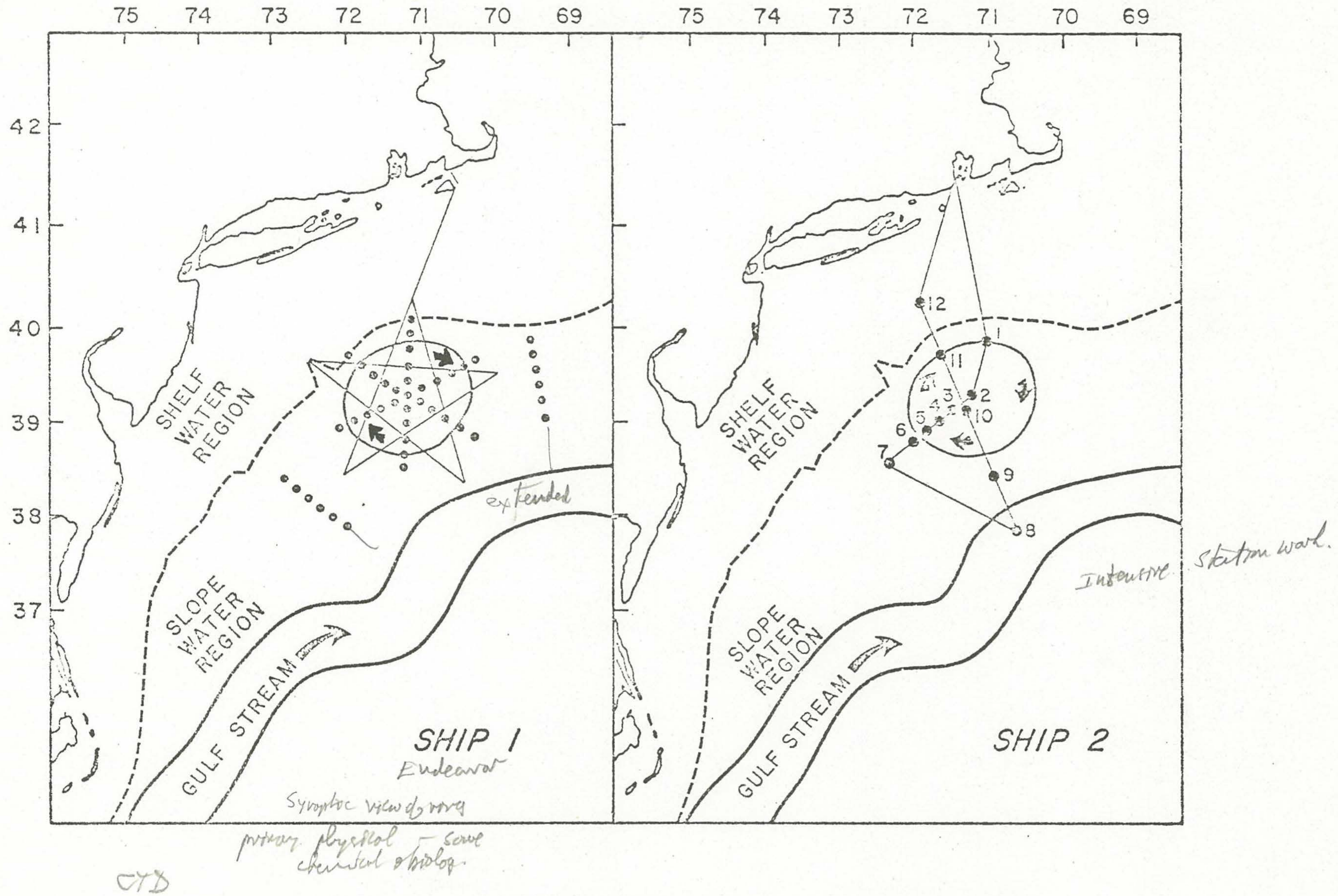


Figure 3. Cruise tracks for ships 1 and 2 for August 1981 and other two-ship operations.

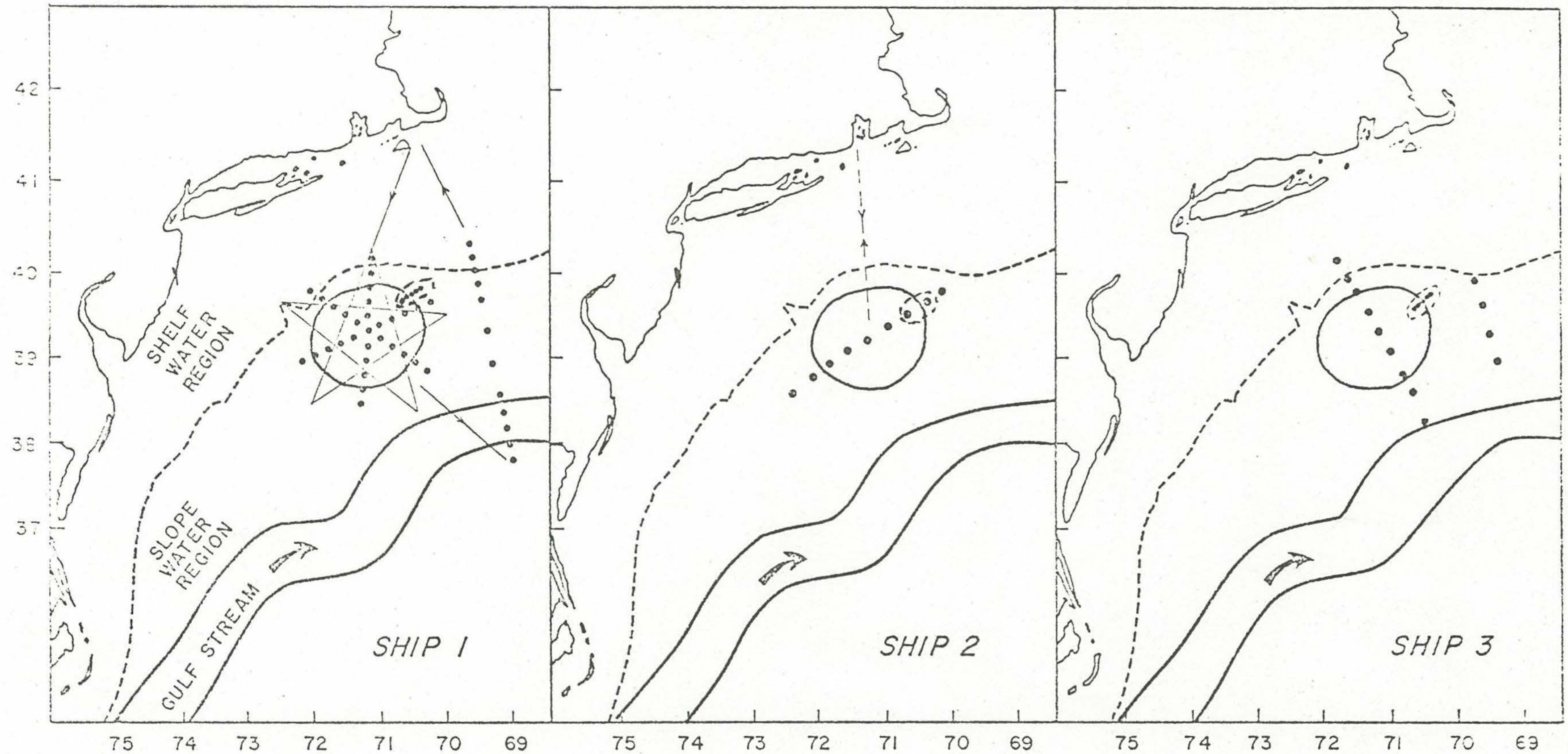


Figure 4. Tentative cruise tracks for a three-ship operation: Cruise days: Ship 1 (21), Ship 2 (18), Ship 3 (18). Dashed area at ring boundary will be site of simultaneous multi-ship study.

pattern for XBTs, three CTD sections through the ring, and continuous measurements of surface or near surface meteorology, physics, and phytoplankton/chlorophyll. It will be the primary ship for physical oceanographic data collection.

Experiments involving nutrient chemistry, particulate matter and plankton physiology will be the principal focus on ship 2, which requires 26 berths. Fewer number of stations (compared to ship 1) will be occupied but typically each will take 36-48 hours to complete.

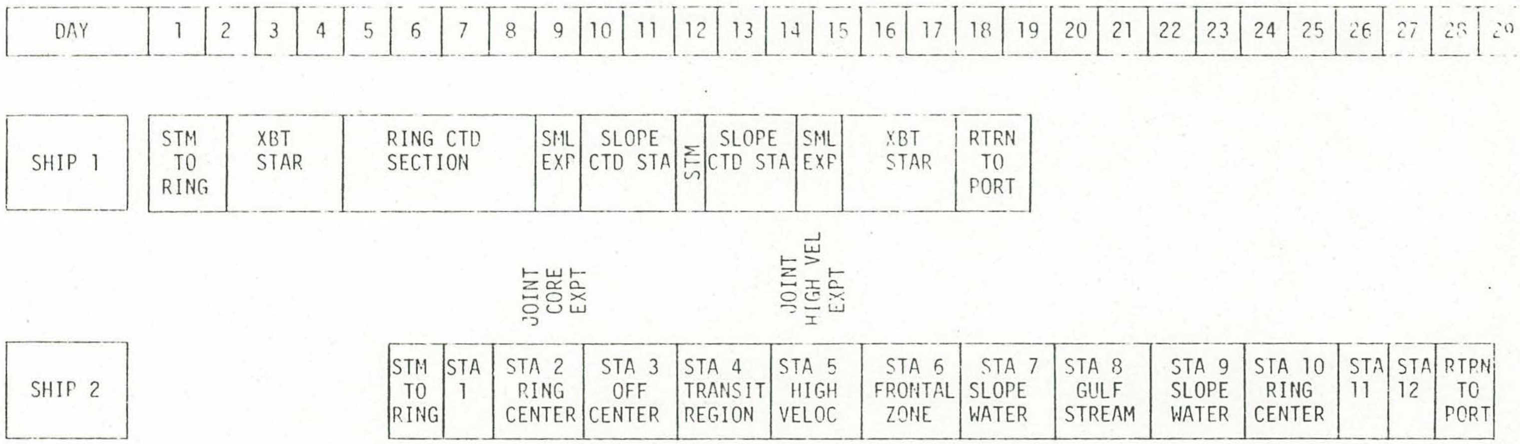
Spatial variability of zooplankton and nekton, and selected radionuclides will be studied from ship 3 with emphasis on the frontal transition regions. Detailed studies using three ships on two of the 1982 cruises will permit a better interpretation of data collected during two ship operations, when activities of ships 2 and 3 will be combined.

On each of the ring cruises joint operations involving all of the ships will be planned for the ring center and the frontal boundary. Measurements outside the ring will be made as needed in order to characterize the Slope Water in which the ring is imbedded. Further scientific justification for the spatial measurement scheme may be sought in the proposals of the roughly two dozen principal investigators in the Warm Core Rings Program. In the next section we show a detailed operational plan for the September 1981 cruises.

5. Operational Plan for 1981

Remote sensing of the Slope Water and Warm Core Rings preceding the field measurements will be utilized to provide a history of sea surface water structure and movement prior to the cruise and to provide the detailed information about the position of a particular ring, the nearby Gulf Stream, and the Shelf Water entrained around the ring periphery. This latter information is needed to complete the planning of the cruise track and station plan at the start of the cruise. Infrared images from satellite sensors will be processed by D. Olson and O. Brown (University of Miami) to provide sea surface temperature maps for the Slope Water region on a weekly basis throughout most of the year. Beginning four weeks preceding the cruise, daily maps will be produced, weather permitting, and unprocessed images will be available during the two or three days before the cruise starts.

The initial field program can best be illutrated by considering a specific work plan for the two ships (Figure 5). Ship 1 will depart on day 1, proceed to the Warm Core Ring selected for the study, and conduct a rapid XBT star pattern of the ring to define its shape and center location. A Loran-C drifter with a particle interceptor trap will be deployed in the center of the ring and the detailed CTD sections will be carried out. On day 9 the two ships will rendezvous at ring center to conduct a small-scale vertical flux experiment in the vicinity of the drifter, which



SHIP 2 SAMPLING PROGRAM AT MAJOR STATIONS

Time Critical Sampling

Activity	Duration	Time Period	
Biological Pattern Assessment			
MOCNESS-1 tow	3.5 hr	0900-1230	daylight
MOCNESS-20 tow	4.0 hr	1230-1630	daylight
MOCNESS-1 tow	3.5 hr	2100-0030	night
MOCNESS-20 tow	4.0 hr	0030-0430	night
Experimental Biology			
30 L Niskin cast	1.5 hr	0500-0630	dawn
Zooplankton grazing	0.5 hr	0630-0700	
Meter net haul	0.5 hr	0700-0730	
Microzooplankton tow	1.0 hr	0730-0830	
30 L Niskin cast	1.5 hr	1130-1300	noon
Meter net haul	0.5 hr	1300-1330	

Non-Time Critical Sampling

Activity	Duration
Deep CTD-O_2 Chemistry	8 hr
Shallow CTD-O_2 Chemistry	3 hr
Large volume filtration	6 hr
Vertical profiling pump	3 hr

Total sampling time committed: 41 hours per station. Remaining 7 hours available for steaming between stations and supplemental sampling.

Figure 5. Work plan for Sept. 1981 with time-line activities for Ship 1 and Ship 2 and the sampling plan aboard Ship 2.

will be equipped with either a cyclosonde or distributed temperature sensor. On day 10 Ship 1 will commence the CTD sections in th Slope Water ahead of the ring (to the southwest) and in the wake of the ring (to the east). On day 14 the two ships will rendezvous in the high velocity region for a second joint small-scale lateral flux experiment and drifter deployment. Upon completion of this work, Ship 1 will conduct a second XBT star pattern of the ring to define changes in its structure over the two week period of the study. The work of Ship 1 will be completed on day 19.

Ship 2 will depart for the ring on day 6 having received information from Ship 1 concerning the location of ring center and temperature features associated with the ring. Station 1 will be taken enroute to ring center to obtain radon samples near the seafloor where the ring may be interacting with the continental rise and slope. Station 2 at ring center will be the first major station and it will occur on days 8 and 9 in conjuntion with the Ship 1 drifter and small-scale experiments. Stations 2-7 will be a transect of major stations along the southwest radius of the ring; each station will require 48 hours. Station 5 will occur on day 14 in the high velocity region in coordination with Ship 1. Station 8 will provide information on the Gulf Stream; stations 7 and 9 will provide data on the Slope Water outside the ring; and station 10 will be a repeat of the ring core measurements 16 days after station 2. Station 11 will provide another set of radon samples to assess the ring-slope interaction and station 12 will provide selected information on the Shelf Water.

The activities aboard Ships 1 and 2 are summarized in Figure 5. The sampling for biological distribution patterns and the experimental biology will occur on alternate days and the sampling which does not depend on the time of day will be interspersed between the other activities at each station.

6. Cooperation with other Groups and Agencies

We include below brief descriptions of how the proposed research on Warm Core Rings will interact with other groups or agencies.

National Marine Fisheries Service

The proximity of the Slope Water and Warm Core Rings to the continental shelf results in the need for cooperation and coordination between Warm Core Rings scientists and those of the National Marine Fisheries Service whose mission in the northwest Atlantic is principally concerned with the assessment and regulation of the living resources of the continental shelf. We have maintained close contact with scientists at NMFS Northeast Regional Laboratory and have identified three areas where coordination of research activities is to take place: (1) interaction of rings with the waters and biota of the continental shelf; (2) relationship of rings to the migration and feeding habits of large pelagic fish such as tunas, sharks, and swordfish; and (3) Slope Water variability and air-sea interaction that may affect or be affected by Rings.

National Aeronautics and Space Administration

A Warm Core Ring offers an excellent site for combined remote sensing and shipboard oceanographic studies. Rings offer large contrasts in surface waves, currents, elevation, and chlorophyll, all of which may be remotely monitored. This would provide oceanographers data throughout the life history of a ring and could provide NASA with shipboard sea truth data useful in evaluating sensing systems such as the ocean color scanner and the synthetic aperature radar. NASA support is being provided for the optical studies of chlorophyll by C. Yentsch and R. Smith and the near-surface velocity profiling of T. Joyce.

7. Management

This program requires effective coordination and management of the individual research components to assure that the objectives will be met. The field work and interpretation of the data will require close interaction among the investigators. The major elements of the organizational structure are a six member executive committee headed by a chairman and a vice-chairman, a program services office, an advisory committee, and five research components comprised of the principal investigators (Figure 6). The chairman will act as spokesman for the program and is responsible for providing program leadership. The vice-chairman will serve as the operational coordinator and will supervise the service office. Other members of the executive committee will assist in coordinating the detailed requirements and activities within each of the five components. The advisory committee will attend general meetings and will advise the executive committee on the state and direction of the program.

There are three phases of activity required in this program: the field measurements, the analysis of data from the individual research efforts, and the integration of the results from each of the research components. The executive committee and the service office will guide these activities and provide basic common services required by the principal investigtors. The Ring Executive Committee will serve as an interdisciplinary group to provide the overall scientific leadership of the program by representing the interests and requirements of the various components of the program and assuring that they constitute a coherent program commensurate with the research opportunities provided by Warm Core Rings. This Executive Committee was selected from among the principal investigators in the program and it is composed of two scientists from each of the three disciplines in the program with at least one person from each research component.

National Science Foundation

Warm Core Rings Executive Committee

Dana R. Kester, Chairman

Peter H. Wiebe, Vice-Chairman

Glenn Flierl
David Schink
Terrence Joyce
James McCarthy

Advisory Committee

Allan Robinson
Derek Spencer
John Knauss
Alan Longhurst

Services Office

Program Services Administrator
Data Processor
Logistics Coordinator
Secretary

Principal Investigators

Physical Oceanography

Otis Brown
Robert Evans
Terrence Joyce
Kevin Leaman
Don Olson
Thomas Osborn

Chemical Distributions and Processes

James Bishop
Dana Kester
David Schink

Spatial Biology

Richard Backus
*Patricia Blackwelder
Raymond Smith
Peter Wiebe
Charles Yentsch
G. Fryxell

Plankton Physiology

Timothy Cowles
Gary Hitchcock
James McCarthy
David Nelson
Michael Roman
Theodore Smayda

Analytical and Numerical Modeling

Glenn Flierl
Joseph Wroblewski

* NSF Funding Pending

Figure 6. Warm Core Rings Organizational Structure.

Communication among the investigators will be an important factor in assuring maximum interdisciplinary accomplishments. Scientific program meetings will be held at least once a year to provide opportunities for the principal investigators to exchange data and ideas, to report on their findings, and to plan the field programs. The first of these meetings will be held in March 1981 soon after the commencement of funding to carry out the detailed planning for the September 1981 field study. The second meeting will be in January 1982 to report the results from the initial field program and to develop plans for the 1982 time series experiment. Subsequent general meetings will be scheduled as illustrated on Figure 2.

Prior to each field effort, a pre-cruise meeting will be convened of all shipboard participants and other investigators having requirements of the field study. We expect to make use of the ATS-3 satellite communication system for ship-to-shore communication during the field studies. In addition to voice communication this capability will include data transfer and printed copy transmission.

A periodic newsletter will be distributed to inform the investigators of the program status and provide a convenient mechanism for rapid reporting of results within the program.

The Program Service Administrator (A. Morton) is responsible for maintaining complete information on the requiremens of the investigators and distributing information within the program. The program service office is located in Room G3 of the Bigelow Building at the Woods Hole Oceanographic Institution (617-548-1400, x2428). Morton will be assisted by a logistics coordinator whose responsibility will be to assure that the program's seagoing equipment needs are known and met by the ship operators. Details such as the characteristics of winches, cranes, shipboard utilities, freight services, and storage facilities required by the principal investigators will be handled by the logistics coordinator. A data processor will establish a computer-based data storage and retrieval system for the program and will attend to the operation of the CTD system at sea on ship 2. Data which are compatible with standardized formats will be maintained in the system and will be accessible to all the principal investigators. These data include measurements of physical and chemical parameters from discrete samples and continuous probes and information on the ships' and rings' position during the field measurements. Data which are not readily placed in standard digital format such as the results of physiological experiments and detailed particle analyses will be indexed by the Service Office with information about its location and status for use by the investigators. The data procesor will arrange for the transfer of data to NODC.

Immediately following each cruise, the Program Service Administrator will prepare an initial synthesis of the field data so that the principal investigators will have a common record of navigational data, ring location relative to each sampling operation, and general information on the ring environment based on shipboard satellite imagery, and remote sensing observations.

References

Bisagni, J., J. 1976. Passage of anticyclonic Gulf Stream eddies through deep water dump site 106, during 1974 and 1975. NOAA Dumpsite Evaluation Rep. 76-1, Department of Commerce, 30 pp.

Halliwell, G. R., Jr. and C. N. K. Mooers. 1979. The space-time structure and variability of the shelf water-Slope Water and Gulf Stream surface temperature fronts and associated Warm-Core eddies. Journal of Geophysical Research, Vo. 84, No. C12, 7707-7725.

Lai, D. Y. and P. L. Richardson. 1977. Distribution and movement of Gulf Stream rings. Journal of Physical Oceanography, 7, 670-683.

Mizenko, D. and J. L. Chamberlin. 1979. Annales Biologiques for the year 1977. ICES publication, H. Tambs-Lyche, ed., pp. 39-44.

Smith, P. C. 1978. Low-frequency fluxes of momentum, heat, salt, and nutrients at the edge of the Scotian Shelf. Journal of Geophysical Research, 83, 4079-4096.