

Impacts of Eddies and Mixing on Plankton Community Structure and Biogeochemical Cycling in the Sargasso Sea

The currents, fronts and eddies that comprise the oceanic mesoscale, sometimes referred to as the “internal weather of the sea,” are highly energetic and ubiquitous features of ocean circulation. Dynamical consequences of these phenomena include perturbation of the chemical and biological environment that can dramatically impact biogeochemical cycling in the ocean. The processes that regulate this response are extraordinarily complex, challenging us to understand how the physical, biological and chemical processes are functionally related.

Recent evidence suggests that mesoscale eddies are an important nutrient transport mechanism in the oligotrophic waters of the main subtropical gyres. Numerical simulations and satellite-based statistical estimates indicate that the magnitude of the eddy-driven nutrient flux could be sufficient to balance geochemical estimates of new production, which far exceed that which can be sustained by traditional mechanisms of nutrient supply. Relatively few direct observations of this process are available, owing to the spatial and temporal intermittency of the events which drive it. Available data demonstrate that isopycnal displacements associated with certain types of eddies can transport nutrients into the euphotic zone, resulting in the accumulation of chlorophyll in the overlying waters. However, the nature of the biological response and its impact on coupled biogeochemical cycles and export has yet to be elucidated. Furthermore, the relationship between eddy-induced upwelling and diapycnal mixing in and below the mixed layer remains obscure; the strength of this interaction determines the degree to which the eddy-driven effects are irreversible and thereby effect a *net* biogeochemical flux.

Our team of investigators proposes to collect a set of measurements that will document phytoplankton physiological response, changes in community structure, export and the biogeochemical ramifications of eddy induced upwelling and mixing in the Sargasso Sea. Target features will be identified prior to field deployment via remote sensing. High resolution surveys will be undertaken with an undulating towed instrument that includes a Video Plankton Recorder and a Fast Repetition Rate Fluorometer. This suite of instruments will facilitate simultaneous assessment of photosynthetic parameters and the species assemblage of phytoplankton and zooplankton. These measurements will be accompanied by discrete water sampling of biogeochemical properties in sets of stations along cross sections of the chosen features. Export will be measured at selected locations within the mesoscale structure. Rates of mixing between the surface mixed layer (order 10m) and waters at the base of the euphotic zone (order 100m) will be inferred from the Helium flux gauge and measured directly with an SF₆ tracer release. Taken together, these observations will be sufficient to test the hypothesis that eddy-induced upwelling increases photosynthetic rates, changes community structure and increases export from the euphotic zone, thereby playing an important role in biogeochemical cycling of the subtropical oceans.

In essence, what is suggested herein is a mechanism by which a highly nonlinear biological response regulates the impact of a physical disturbance on biogeochemical cycling. We plan to incorporate what we learn about the nature of this regulation into basin-scale eddy-resolving models of the North Atlantic in order to investigate the impacts of this coupled physical–biological–chemical dynamic on large-scale biogeochemical distributions. We hypothesize that geophysical turbulence causes a net acceleration of elemental cycling that plays a fundamental role in maintaining the mean biogeochemical state of the ocean.

The proposed research is to be carried out in a collaborative effort amongst ten principal investigators from five institutions: Woods Hole Oceanographic Institution, the Bermuda Biological Station for Research, Rutgers University, University of California, Santa Barbara, and the University of Miami. The work plan consists of two years of field observations followed by a final year of synthesis. The total amount requested is \$3,407,311.

Results of Prior NSF Support

Dennis McGillicuddy is currently supported by NSF under the U.S. JGOFS Synthesis and Modeling Program to study the role of mesoscale processes in basin-scale biogeochemical budgets of the North Atlantic. He is also funded in the U.S. Globec Georges Bank Program to investigate coastal circulation and zooplankton population dynamics. Thus far, these projects have resulted in more than 20 publications (including those submitted and in press).

Ken Buesseler has received NSF support since 1987. Of particular relevance to this proposal are those grants which use natural radionuclides as tracers of upper ocean export. This work has been conducted primarily under the JGOFS Program resulting in over 20 JGOFS-related publications to date (full CV at <http://cafethorium.whoi.edu>).

Nick Bates was recently supported by NSF to study carbon cycling and air-sea gas exchange of CO₂ in the Sargasso Sea. This project has resulted in 21 publications. He is a co-PI of the BATS grant and is also funded by 2 JGOFS SMP projects to study the production and remineralization of DOC and the global seasonal variability of inorganic carbon.

Cabell Davis and Scott Gallager were funded by NSF in Phase II of the U.S. Globec Georges Bank Program to measure the transport of Calanoid copepods across the boundaries of Georges Bank. Analysis of the data from four cruises (composed of 2668km of track line and 526 hours of video tape) is ongoing. Thus far, this grant had led to eight publications with two more submitted.

From 1976 to 1998, P. Falkowski and Z. Kolber were employed by a Federal Research Laboratory, and as such were ineligible for direct NSF support. Nonetheless, during this period, both PIs and their research group helped contribute to NSF-supported ocean science programs. In particular, with financial support from the Department of Energy and NASA, the PIs worked in collaboration with the Moss Landing Marine Laboratory and contributing groups on both IRONEX experiments. The results of these efforts were summarized in three papers in *Nature*.

Dennis Hansell investigates the cycling of carbon and nitrogen, with particular focus on the dissolved organic fractions. He has been supported by US JGOFS (BATS, Arabian Sea and Southern Ocean) as well as NOAA OACES (North Atlantic, South Pacific, Indian Ocean). Publications resulting from these projects address subjects such as basin and global distributions and turnover of DOC/N, net community production of DOC, DOC mineralization, DOC export, and AOU development in the main thermocline.

William Jenkins has made significant contributions to the development and use of tritium-³He dating in the oceans. Using this technique, he has determined rates of water mass renewal, oxygen utilization rates and primary production, oxygen production rates, diapycnal and isopycnal mixing rates, climatic changes in water mass renewal rates, subduction rates, tracer granularity, and vertical nutrient transport. He has improved tritium detection limits by more than an order of magnitude and used tritium to study abyssal ventilation and deep western boundary currents.

James Ledwell has led a series of tracer release experiments in the stratified ocean with funding from NSF, most recently the Brazil Basin Tracer Release Experiment at 4000 meters depth from 1996 to 2000. Most pertinent to the present proposal was the North Atlantic Tracer Release Experiment, which gave a definitive 2.5 year average of diapycnal diffusivity at 300 to 400 meters in the pycnocline of the North Atlantic, while it measured lateral dispersion on scales from less than 1 km to nearly 1000 km.

David Siegel investigates the interactions among physical, biological, biogeochemical and optical oceanographic processes. He is the coPI of the Bermuda BioOptics Program (BBOP) which has been collecting optical profile data in collaboration with the BATS program since 1992. Initial support for BBOP came from NSF.

1. Introduction

Ocean biogeochemical cycles and physical processes control the flux of carbon and associated bio-elements between the ocean and its atmospheric and terrestrial boundaries. The complex linkages and feedbacks between physical forcing (light, currents, mixing), biological systems (species composition and functionality) and geochemical cycling (solubility, sorption, bioutilization) make it extremely difficult to quantitatively predict and model ocean biogeochemical cycles. Simple models that assume single limits to plankton growth or steady-state physical forcing, fail to simulate major features of observed distributions. For example, current evidence suggests that carbon and nutrient cycles in the upper ocean cannot be balanced with traditional mechanisms of nutrient supply, such as derived from winter mixing and vertical diffusion. One recent alternative for the oligotrophic waters of the subtropical gyres is that mesoscale eddies are an important mode of nutrient transport (McGillicuddy *et al.*, 1998). This finding is based on relatively few direct observations of the process, together with estimates of the magnitude of eddy-driven nutrient flux from numerical models and satellite-based statistical estimates.

The eddy upwelling mechanism can be conceptualized by considering a density surface with mean depth coincident with the base of the euphotic zone (Figure 1). This surface is perturbed vertically by the formation, evolution and destruction of mesoscale features. Shoaling density surfaces lift nutrients into the euphotic zone which are rapidly utilized by the biota. Deepening density surfaces serve to push nutrient-depleted water out of the well-illuminated surface layers. The asymmetric light field thus rectifies vertical displacements of both directions into a net upward transport of nutrients which are fixed into organic material. This upward flux must be balanced by a commensurate export of that material or its derivative products (*i.e.*, dissolved organic matter).

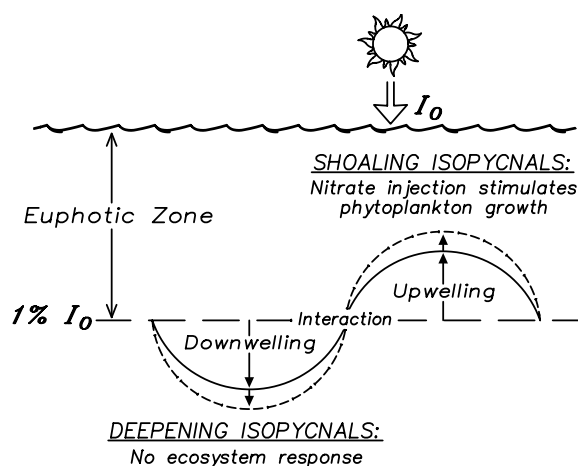


Figure 1: A schematic representation of the eddy upwelling mechanism. The solid line depicts the vertical deflection of an individual isopycnal caused by the presence of two adjacent eddies of opposite sign. The dashed line indicates how the isopycnal might be subsequently perturbed by interaction of the two eddies. Redrawn from McGillicuddy *et al.* (1998).

We seek to understand the mechanism by which a highly nonlinear biological response regulates the impact of a physical disturbance on ocean biogeochemical cycling. Observations using remote sensing will be used to find target eddy features for study. A suite of detailed measurements will document the physical manifestation of the eddy disturbance, the rate of mixing in the upper ocean, physiological response of the phytoplankton, changes in community structure, export and the biogeochemical ramifications of eddy induced upwelling in the Sargasso Sea. We plan to incorporate what we learn about the nature of this regulation into basin-scale eddy-resolving models of the

North Atlantic in order to investigate the impacts of this complex coupled physical–biological–chemical dynamic on large-scale biogeochemical distributions. We hypothesize that the aggregate response to the field of geophysical turbulence is a net acceleration of elemental cycling that plays a fundamental role in maintaining the mean biogeochemical state of the ocean.

2. Scientific Background

New production in the ocean is that fraction of total primary production which is fueled by nutrients from outside the euphotic zone (*e.g.*, Dugdale and Goering, 1967). The magnitude of this quantity is of considerable interest from the point of view of biogeochemical cycling because it sets a fundamental constraint on the amount of biogenic material that can be exported via the so-called biological pump. The fact that geochemical estimates of new production in the oligotrophic waters of the open ocean far surpass that which can be sustained by traditional mechanisms of nutrient supply has been problematic for some time (Shulenberger and Reid, 1981; Jenkins and Goldman, 1985). Three independent transient tracer techniques all indicate that new production in the Sargasso Sea is on the order of $0.5 \text{ mol N m}^{-2} \text{ yr}^{-1}$: oxygen production in the euphotic zone (Jenkins and Goldman, 1985; Spitzer and Jenkins, 1989; Sarmiento *et al.*, 1990); oxygen consumption in the aphotic zone (Jenkins and Goldman, 1985; Jenkins and Wallace, 1992), and the Helium flux gauge (Jenkins, 1988a). Approximately one quarter to one third of the annual nutrient requirement can be supplied by entrainment into the surface mixed layer caused by wintertime convection (Michaels *et al.*, 1994b). Modern estimates of mixing rates in the thermocline (Lewis *et al.*, 1986; Ledwell *et al.*, 1993; Ledwell *et al.*, 1998) combined with the observed nutrient gradient at the base of the euphotic zone suggest that diapycnal diffusion contributes very little. Wind-driven vertical motion in the main subtropical gyre is oriented downward due to the negative wind stress curl in the region and therefore represents a nutrient sink rather than a source. The surface Ekman drift does advect nutrients horizontally toward the interior of the gyre, but recent calculations suggest the net contribution of the wind driven transport is positive but small (Williams and Follows, 1998). Together these processes account for less than one half the annual nutrient budget.

The notion that mesoscale processes could be an important vehicle for nutrient transport in the world's oceans has been debated for some time (*e.g.* Woods, 1988; Fasham *et al.*, 1985; Franks *et al.*, 1986; Venrick, 1990; Falkowski *et al.*, 1991; Strass, 1992; Flierl and Davis, 1993; Dadou *et al.*, 1996; Smith *et al.*, 1996; Allen *et al.*, 1996; Oschlies and Garçon, 1998; Spall and Richards, 2000; Mahadevan and Archer, 2000). Comparison of two hydrographic profiles sampled one month apart in the summer of 1986 off Bermuda documented an apparently eddy-driven nutrient injection event that could account for 20-30% of the annual new production (Jenkins, 1988b). In the decade that has passed since those observations were first published, substantial evidence has accumulated that mesoscale eddies are the dominant mode of nutrient transport in the Sargasso Sea (McGillicuddy *et al.*, 1998). High resolution regional numerical simulations in this area suggest eddy-induced upwelling causes intermittent fluxes of nitrate into the euphotic zone of sufficient magnitude to balance the nutrient demand implied by geochemical estimates of new production (McGillicuddy and Robinson, 1997). Nitrate flux calculations based on satellite altimetry and a statistical model linking sea level anomaly to subsurface isopycnal displacements provide estimates of comparable order (Siegel *et al.*, 1999). Observations of a nutrient pulse associated with a mesoscale eddy were obtained using novel chemical sensing technology deployed on the Bermuda Testbed Mooring (McNeil *et al.*, 1999). Analysis of BATS hydrographic data with a one-dimensional model revealed month-to-month variability that cannot be explained by local air-sea fluxes; these anomalies are almost certainly associated with mesoscale advection (Doney, 1996). Mesoscale biogeochemical surveys carried out as part of the BATS Validation activities have documented the impact of

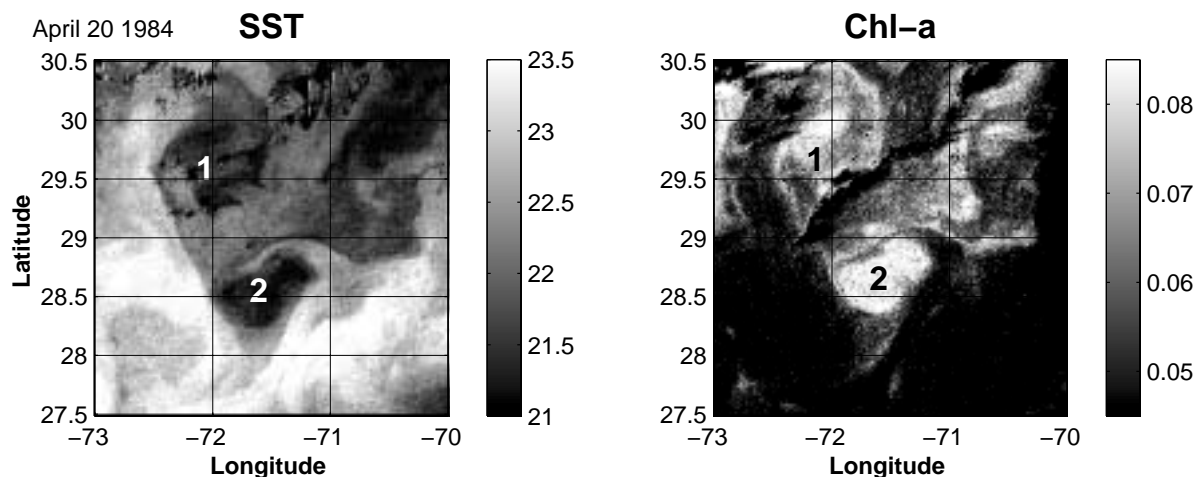


Figure 2: Simultaneous images of AVHRR sea surface temperature ($^{\circ}\text{C}$) and CZCS-derived pigment biomass (mg Chl m^{-3}) in the Sargasso Sea on April 20, 1984. The two eddy features exhibit cold sea surface temperature anomalies and enhanced chlorophyll, consistent with the eddy upwelling mechanism.

mid-ocean eddies on nutrient and biomass distributions. These observations demonstrate that eddy-induced upward displacement of density surfaces can inject nutrients into the euphotic zone which results in the accumulation of phytoplankton biomass in the overlying waters (McGillicuddy *et al.*, 1999). Similar patterns emerge from an analysis of satellite-derived sea-surface temperature and pigment fields (McGillicuddy *et al.*, 2001). Analysis of the 21 instances during the lifetime of the Coastal Zone Color Scanner (CZCS) in which simultaneous AVHRR and ocean color images are available show that higher (lower) pigment biomass occurs in mesoscale features consisting of cold (warm) temperature anomalies (Figure 2). This covariation in property distributions demonstrates that the impact of the eddies extends all the way to the surface.

The eddy upwelling mechanism described above is an adiabatic process. Once an isopycnal surface has been lifted into the euphotic zone, it will eventually relax back to its mean position. Therefore, this process by itself does not provide a means for seasonal oxygen accumulation within the euphotic zone nor excess ^3He in the mixed layer, as is observed. Some mixing must be involved to allow these signals to be “left behind” eddy induced nutrient flux events. Thus, the relationship between thermocline displacements and diapycnal fluxes in and just below the surface mixed layer (including entrainment) remains as one of the most important areas for further research. It is clear from sea surface temperature and ocean color imagery that mesoscale features often impinge upon the mixed layer (Figure 2). However, the details of how the deep ocean communicates with the near-surface layers remain largely unknown.

Perhaps equally obscure are the mechanisms that regulate the biological response to physical disturbances such as those caused by eddies. It has been argued that planktonic community structure in oligotrophic systems is remarkably stable (*e.g.*, Goericke, 1998). However, a variety of evidence from the Sargasso Sea and other oligotrophic subtropical gyres suggests that physical perturbations can lead to dramatic shifts in species composition. For example, Goldman (1988) suggested the “spinning wheel” concept in which the background state of the biological system is dominated by very small phytoplankton growing primarily on nutrients that are recycled through the microbial loop. This state is episodically perturbed by the input of nutrients to the base of the euphotic zone, causing a shift in phytoplankton species composition from picoplankton toward much larger cells such as diatoms. In such a scenario, these large cells would sink rapidly once the

nutrient enhancement was depleted, thereby contributing a disproportionately large fraction of new versus total primary production. Laboratory culture experiments have confirmed that diatoms can grow sufficiently rapidly to produce significant blooms, even at the low light levels characteristic of the base of the euphotic zone (Goldman *et al.*, 1992; Goldman, 1993). Significant silica production has also been measured directly in the Sargasso Sea (Brzezinski and Kosman, 1996). Thus, differing ecological responses to physical perturbations will lead to differential uptake and removal of carbon and major bioactive elements such as nitrogen, phosphorus and silicon.

Episodic shifts in species composition have been observed in the field. McNeil *et al.* (1999) documented an increase in diatom pigments that coincided with an eddy event at the BATS site in July-August of 1995. Letelier *et al.* (2000) synthesized a variety of data from the shipboard time-series, moored sensors and satellite-based instruments to describe the passage of a mesoscale feature past the Hawaiian Ocean Time-series (HOT) site during the spring of 1997. That event resulted in a three-fold enhancement in 0-25m chlorophyll concentration, and an increase in the 0-100m inventory of nitrate plus nitrite of *more than four orders of magnitude*. In addition, the relative contribution of diatoms to the standing stock of chlorophyll-a increased twofold in the interior of the eddy. Such variations in the abundance of diatoms are not uncommon in the HOT record (Scharek *et al.*, 1999a,b). Brzezinski *et al.* (1998) observed enhanced diatom production in the interior of a cyclonic eddy approximately 200km north of the HOT site. Indeed, the impact of mesoscale features on species composition has been observed in a variety of contexts (*e.g.* Gulf Stream and Kuroshio Rings – Wiebe and Joyce, 1992; the PRIME eddy – Savidge and Williams, 2001).

Although the evidence documented in the literature is substantial, it consists mostly of a collection of targeted studies which treated individual aspects of the system at different places and at different times. What is needed to make progress on this enormously complex problem are integrated interdisciplinary investigations that will allow us to deduce the underlying mechanistic controls. Only then will we be in a position to assess the impact of mesoscale eddies on the mean properties of the coupled physical-biological-biogeochemical system.

3. Problem Statement

The results described above have documented eddy-driven transport of nutrients into the euphotic zone and the associated accumulation of chlorophyll. However, several key ramifications of mesoscale upwelling events remain unresolved by the extant database, including: (1) phytoplankton physiological response, (2) changes in community structure, (3) impact on export out of the euphotic zone, (4) rates of mixing between the surface mixed layer and the base of the euphotic zone, and (5) implications for biogeochemistry and differential cycling of carbon and associated bioactive elements. This leads to the following hypotheses concerning the complex, non-linear biological regulation of elemental cycling in the ocean.

H₁: Eddy-induced upwelling, in combination with diapycnal mixing in the upper ocean, introduces new nutrients into the euphotic zone.

H₂: The increase in inorganic nutrients stimulates a physiological response within the phytoplankton community.

H₃: Differing physiological responses of the multitude of species present bring about a shift in community structure.

H₄: Changes in community structure lead to increases in export from, and changes in biogeochemical cycling within, the upper ocean.

There are several scenarios in which this chain of hypotheses could be linked or broken. These include, but are not necessarily limited to, the following:

- S_1 : Nutrient input to the euphotic zone simply increases the rate of production by the background species assemblage which is dominated by picoplankton; impacts on biogeochemical cycling are nil.
- S_2 : Increased nitrate availability stimulates a bloom of diatoms; silica-rich organic material produced in the bloom sinks rapidly out of the euphotic zone once the nutrients are exhausted.
- S_3 : Shoaling isopycnals transport dissolved inorganic phosphorus closer to the surface, facilitating nitrogen fixation by *Trichodesmium* spp. or perhaps vertically migrating diatoms with symbiotic bacteria; nitrogen-rich organic material produced during the bloom is exported primarily in dissolved form.
- S_4 : The eddy feature accommodates a change in community structure and biomass of consumers that produce rapidly sinking particles.

Evidence for all these responses have been observed in the Sargasso Sea. McNeil *et al.* (1999) documented changes in pigment composition consistent with a shift toward a diatom-dominated phytoplankton assemblage which coincided with the passage of a mesoscale eddy at the BATS site. Visual observations of an intense bloom of *Trichodesmium* spp. were made inside a cyclonic eddy during BATS validation cruises in 1997 (see below). Abundance of some species of zooplankton were markedly higher within eddies on these same BATS cruises, and it is well known that some shifts in zooplankton species composition/biomass can lead to increased vertical fluxes (e.g. Michaels and Silver, 1998; Anderson, 1998). All of these scenarios could have a profound effect on export and upper ocean biogeochemistry of carbon, nitrogen, phosphorus, and silicon.

4. Objectives

Testing the above hypotheses requires a combination of physical, biological, and chemical oceanography, together with remote sensing and numerical modeling. Thorough space/time sampling of eddy features and integration across multiple components are necessary to elucidate the important controls and feedbacks for quantitative prediction and extrapolation to basin and global scales. The following objectives are proposed to ascertain which of the potential scenarios (S_1 – S_4) may contribute to the complex regulation of biogeochemical cycling in the ocean.

1. Measure the enhancement of inorganic nutrient availability in the euphotic zone brought about by eddy-induced upwelling.
2. Measure the magnitude of phytoplankton physiological response to the increase in nutrients.
3. Assess any shifts in species composition associated with the eddy disturbance.
4. Quantify the impact of the physical, biological and chemical ramifications of the eddy disturbance on upper ocean biogeochemical cycling. This includes measurements of elemental inventories, primary production and export.
5. Assess the interaction between isopycnal transport processes (eddy driven upwelling) and diapycnal fluxes in and below the mixed layer. This holds the key to determining the degree to which the biogeochemical impacts of eddy induced upwelling are reversible.

6. Incorporate what is learned into a basin-scale eddy-resolving model of the North Atlantic to assess the impact of this biological and biogeochemical complexity on large-scale elemental cycles in the ocean.

5. Overview of Proposed Research

We have assembled an interdisciplinary team of scientists to combine quantitative field observations with modeling to study a highly nonlinear biological response to physical disturbances that impact local biogeochemical cycles. The aggregate response to these events is important in maintaining the mean biogeochemical state of the global ocean. Education and outreach activities are planned to highlight the theoretical, observational, modeling and remote sensing aspects of this project.

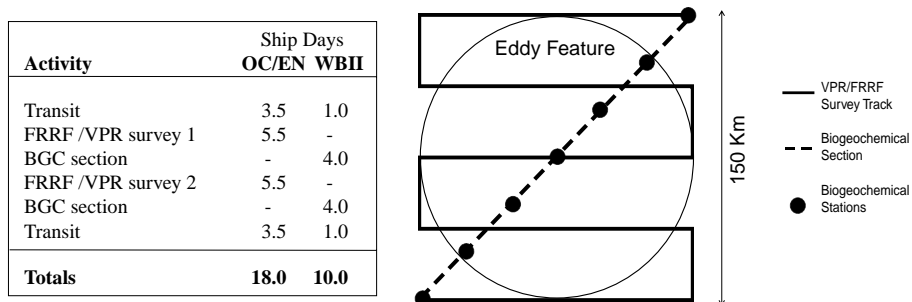
We propose to make a set of observations which consists of two sets of summertime cruises in each of two field years. The June-September time frame was chosen to coincide with a season in which vertical excursions of the mixed layer are at a minimum (except, of course, during hurricanes). This will maximize our ability to separate the effects of eddy-driven upwelling and diapycnal mixing. Mesoscale features will be identified prior to (and tracked during) the seagoing work via the synthesis of satellite altimetry, AVHRR sea surface temperature, and SeaWiFS ocean color measurements in a data-assimilative coupled physical-biological model¹. A series of synoptic surveys of the evolving features will be collected with an undulating towed vehicle equipped with a combined Fast Repetition Rate Fluorometer (FRRF) / Video Plankton Recorder (VPR) package, together with *in situ* flow cytometry of surface water via the ship's through-hull intake. This suite of measurements will facilitate simultaneous assessment of photosynthetic activity and species composition (including large phytoplankton as well as zooplankton). Towed instrumentation such as this provides perhaps the only practical means of ascertaining the three-dimensional physical and biological structure of a mesoscale eddy (*ca.* 150km in diameter) within a time period short enough that the feature will not have changed appreciably (*ca.* 1 week). These high-resolution surveys will be supplemented with traditional hydrographic measurements of dissolved and particulate materials, ¹⁴C productivity, and ³He distributions. Thorium-based radionuclide assays will be used to estimate particulate export of carbon, nitrogen and biogenic silica.

A timeline for each set of survey cruises is outlined in Figure 3. Execution of the plan will be most efficient if the various components are divided between an Oceanus/Endeavor class vessel for survey operations and the Weatherbird II for station work along transects. Prior to the ship's departure, the target eddy will be identified via remote sensing. Analysis of satellite data suggests that there is always a multitude of suitable eddy features in the Sargasso Sea (see <http://science.whoi.edu/users/mcgillic/tpd/tpd.html>). Indeed, we have successfully executed such targeted sampling in this region before (see section 6.1 below). Once the ship arrives at the target eddy, a VPR/FRRF survey will be undertaken in a "radiator" pattern (Figure 3) which will take approximately five and one-half days to occupy. The spatial extent of this pattern is designed to provide intensive coverage within the eddy, in addition to sampling waters outside the feature (which can in some ways be interpreted as the "control" for this natural perturbation experiment). The towed measurements of upper ocean structure (0-200m) will be supplemented with alongtrack XBTs (0-700m) in order to quantify the main thermocline signal. Underway ADCP

¹The use of satellite-based feature tracking to aid seagoing observational programs has a long history within oceanography that dates back at least to the early 1980s with the Warm-Core Rings program. Since that time, the deployment of additional satellite platforms and measurements has expanded that capability dramatically. Two of the PIs (McGillicuddy and Siegel) have experience in such undertakings; one example in the Sargasso Sea is discussed in some detail below.

measurements will be used to map the velocity field. Next, a section of biogeochemical stations will be occupied along a strategically chosen diameter of the eddy. The entire procedure will then be repeated to ascertain the temporal evolution of the feature on the 1-2 week time scale characteristic of synoptic dynamical events (such as eddy-eddy interactions) characteristic of this region. In addition, an instrumented drifting buoy array will be deployed in the eddy in order to assess changes in physical and bio-optical parameters between the two surveys.

Figure 3: Proposed sampling operations for each set of cruises (two per field year).

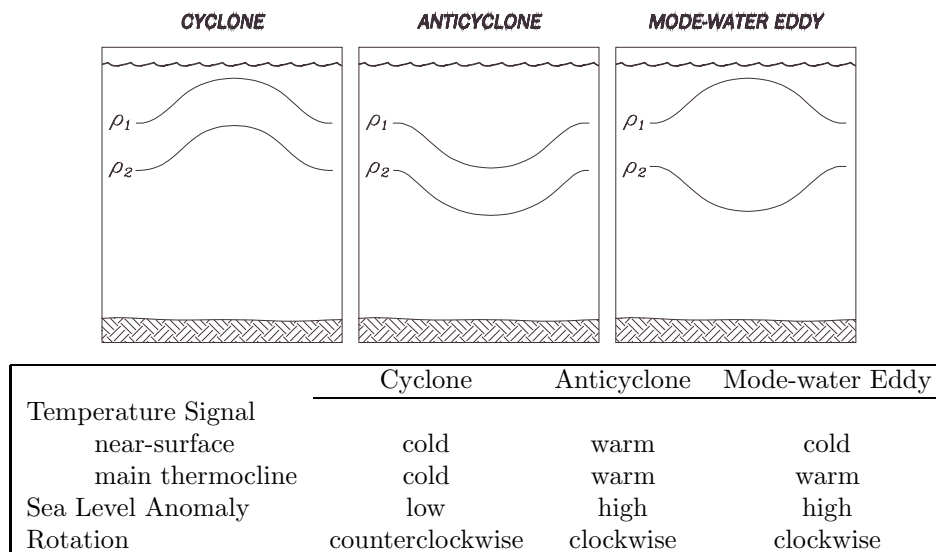


Of course the time scale of eddy interactions is not the only one relevant to the problem. Perhaps even more important is the question of the eddy’s developmental stage within its lifetime. For example, a newly forming or intensifying cyclone will actively upwell nutrients, whereas a decaying feature of the same type will actually downwell the previously perturbed density surfaces. These fluctuating aspects intrinsic to the formation and decay of individual eddies have dramatic consequences with respect to ecosystem dynamics and biogeochemical cycling (e.g. Nelson *et al.*, 1989; Sweeney *et al.*, submitted). Thus it is critical that the same feature be sampled during at least two stages of its lifetime. Given typical eddy lifetimes of several months in this region (Richardson, 1993), a second experiment scheduled approximately three weeks after the first would be ideal: enough time will have elapsed so that the eddy will have changed, yet not so long that the feature is likely to have been destroyed. Fortunately, satellite altimetry and the drifting bio-optical buoy array will provide the means for tracking temporal changes in the feature during the intervening period.

There are at least two types of eddies in the Sargasso Sea² which can upwell nutrients into the euphotic zone (Figure 4). In a typical mid-ocean cyclone, doming of the main thermocline results in displacement of the seasonal thermocline toward the surface. A similar disturbance of the upper ocean density structure can be effected by so-called Mode-water eddies. These thick lenses of 18-degree water raise the seasonal thermocline and depress the main thermocline. These features are generally associated with anticyclonic rotation because their displacement of the main thermocline overshadows that of the seasonal thermocline in terms of geostrophic shear. In principle, these two types of eddies are distinguishable with a combination of satellite altimetry and AVHRR: both will have cold surface temperature anomalies, while the sea level displacements will be of opposite sign: negative for cyclones and positive for Mode-water eddies. Two field years are proposed so that one eddy of each type can be studied.

²From a physical oceanographic standpoint, eddies in the Sargasso Sea are among the best studied anywhere in the world ocean. This region was home to some of the first programs (MODE and POLYMODE) focused on the study of mesoscale processes (Richman *et al.*, 1977; The MODE Group, 1978; Robinson, 1983). The physics of eddies in this region have been the subject of numerous investigations since then, but quantitative information on the biogeochemical impacts of these features has come to light only recently.

Figure 4: Top: Schematic diagram of the isopycnal displacements associated with three types of eddies. Two density surfaces are depicted: one in the seasonal thermocline (ρ_1), and one in the main thermocline (ρ_2). Bottom: Summary of the eddies' physical oceanographic characteristics.



Our strategy for studying the relationship between eddy-induced upwelling and diapycnal mixing is twofold. First, ^3He measurements will be taken along each biogeochemical section in both field years; comparison of this biologically inert tracer to more reactive chemical species such as nutrients, oxygen and carbon will facilitate inference of the rates of vertical mixing and exchange. Second, we will measure the impact of both vertical and horizontal mixing processes directly with an SF_6 tracer release experiment during the first field campaign. Although budgetary constraints allow for only one tracer release, we plan to seek additional partnerships to include such a component in the second field year as well.

6. Program Elements

The following outlines the individual elements of our research strategy, which is summarized in the adjacent table. We believe that an integrated plan of observations and modeling is crucial to the success of the effort. The team of investigators that has been assembled brings with it the interdisciplinary perspective and advanced technologies necessary to tackle this complex coupled problem.

6.1 Remote Sensing

Eddy features will be monitored prior to and during the field campaigns with a combination of satellite altimetry, AVHRR and ocean color. Because altimetry is not affected by the presence of clouds, it is the most reliable method of feature tracking. Such techniques have been used to

Survey Operations	
VPR	Davis
FRRF	Falkowski
ADCP	Ledwell
XBT	McGillicuddy
Tracer Release	
SF_6	Ledwell
Transect Lines	
$\text{NO}_3/\text{PO}_4/\text{SiO}_2/\text{O}_2$	Bates
HPLC pigments	Bates
^{14}C productivity	Bates
$\text{TCO}_2/\text{pCO}_2/\text{O}_2$	Bates
DOC/DON/DOP	Hansell
$\delta^{15}\text{N}$ (PON)	Hansell
Helium flux gauge	Jenkins
Thorium export	Buesseler
Bio-optics	Siegel
Lagrangian Observations	
Bio-optical drifter	Siegel
Pop-up floats	Ledwell
Remote Sensing and Modeling	
Satellite data	Siegel
Modeling and synthesis	McGillicuddy

provide spatial context for interdisciplinary field studies in the past, such as the JGOFS North Atlantic Bloom Experiment (Robinson *et al.*, 1993; McGillicuddy *et al.*, 1995). Satellite altimetry has also been used by members of this proposal team to site mesoscale surveys conducted as part of the BATS validation activities (McGillicuddy *et al.*, 1998). Several web sites make available near real time data streams from Topex/Poseidon and ERS-2 altimeters (see for example http://www-ccar.colorado.edu/~realtime/global_data_ssh/ssh.html). Sea level anomaly (SLA) estimates from such sources were objectively analyzed prior to and during two cruises in 1997 in order to orient sampling patterns with respect to hydrographic features (Figure 5). The analysis constructed just prior to departure of the R/V Weatherbird II on July 1st showed the area around the BATS site to be relatively quiescent. However, there was an intense interaction occurring between a pair of eddies about a 24hr steam to the northeast of Bermuda. A survey of the cyclonic feature revealed large-amplitude vertical displacements of the temperature and nitrate surfaces in the interior of the eddy (Figure 5). Water parcels from as deep as 350m appear to have been in contact with the base of the euphotic zone (~95m). The effects of this disturbance on the plankton ecosystem were dramatic. Nutrient concentration at 120m in the core of the eddy was increased more than tenfold. Phytoplankton biomass was significantly enhanced in the overlying waters (not shown).

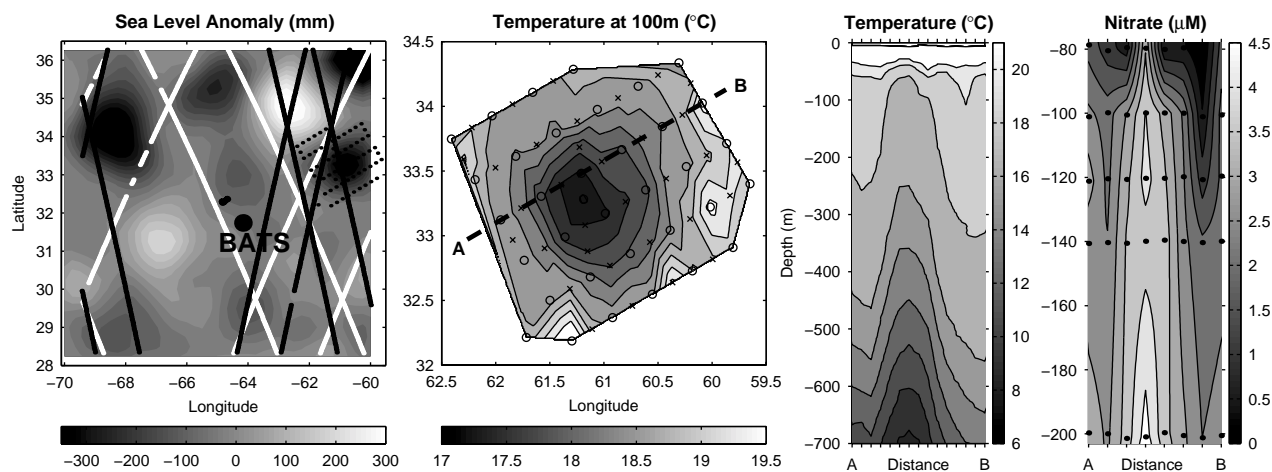


Figure 5: Results from BATS Validation cruise 18, 7-13 July 1997. (a) Satellite-derived map of sea level anomaly for 1 July 1997. Shipboard sampling locations are indicated by dots. Ground tracks for Topex/Poseidon and ERS-2 altimeters are shown as white and black lines, respectively. (b) Temperature at 100m derived from the shipboard measurements. (c) Temperature cross-section along the line indicated in (b). (d) Nitrate cross-section along the line indicated in (b). Note the change in vertical scale between panels (c) and (d).

Satellite data sets will be used to provide a spatial and long-term temporal context for the observational program. Local-area coverage (1 km) AVHRR SST and SeaWiFS ocean color imagery will be collected and processed in real time by the BBSR satellite laboratory (see <http://www.bbsr.edu/satellite/>). Retrospective comparisons between SST and CZCS-derived chlorophyll have revealed the surface signature of eddies in this region (Figure 2; see McGillicuddy *et al.*, 2001b). However, satellite ocean color data are somewhat limited in how they can be applied to assess biological and biogeochemical processes. For example, these data are not capable of distinguishing among phytoplankton pigment types for making chemotaxonomic identification of species (*e.g.*, Garver *et al.*, 1994). They are useful for assessing chlorophyll and colored dissolved

organic material (CDOM) concentrations. The optical properties of the Sargasso Sea are significantly influenced by CDOM, and a summertime subsurface CDOM maximum lies just beneath the seasonal pycnocline (Siegel and Michaels, 1996; Nelson *et al.*, 1998). Fortunately, the CDOM signal can be differentiated from chlorophyll by the SeaWiFS sensor (Garver and Siegel, 1997; Maritorea *et al.*, 2002; Siegel *et al.*, in press). We will therefore be able to distinguish plant pigments that are produced locally in response to eddy upwelling from simple vertical advection of the subsurface CDOM maximum. At each station along the biogeochemical sections (Figure 3), ocean optics observations will be made.

In order to resolve temporal changes between the two intensive sampling periods, an instrumented drifting buoy array will be placed in the center of the feature. The buoy will be instrumented with 3 WETLabs ECO chlorophyll fluorometers, 10 SeaBird SBE-39 temperature sensors and 2 Biospherical Instruments MER-2020 moored spectroradiometer systems distributed through the upper 100 m of the water column. These data will be used to assess changes in phytoplankton pigment biomass, upper ocean thermal structure and relevant ocean optical quantities such as chlorophyll fluorescence, CDOM, and optical backscatter. The array is expected to remain trapped within the eddy during the 2 to 3 weeks between surveys. The surface float will have a light, VHF radio transponder and an ARGOS transmitter.

6.2 *Phytoplankton Physiological Response*

Biophysical studies of nutrient limitation have revealed common diagnostic signals, reflecting changes in the stoichiometry of molecular components in photosystem II (hereafter PSII), and disruption in electron transport within the photosynthetic apparatus. One of the best studied of the biophysical processes is variable fluorescence, which, at room temperature, emanates from PSII (Falkowski and Kiefer, 1985; Krause and Weis, 1991; Owens, 1991). Our group has identified three alterations in the signal that, together, comprise a diagnostic profile indicative of nutrient limitation. These are: (1) a reduction in the change in the quantum efficiency of variable fluorescence resulting from an increase in the intrinsic yield, F_0 ; (2) a reduction in the rate of decay of variable fluorescence in the microsecond time domain; and (3) a change in the functional absorption cross section of PSII. The first signal reflects a reduction in the total number of functional reaction centers relative to the antenna pigments. The second signal reflects retardation of electron transfers from QA to the plastoquinone pool and the rate of oxidation of plastoquinol. The third factor is related to the chlorophyll content of the light harvesting complex of PSII, the probability of sharing absorbed excitation energy between reaction centers, and the energetic coupling between reaction centers and their light harvesting antenna complexes (Greene *et al.*, 1991; Greene *et al.*, 1992; Vassiliev *et al.*, 1995; Falkowski and Raven, 1997). The extent of nutrient and recovery limitation can be related to the three processes. All of these biophysical variables can be precisely and rapidly measured at sea in real-time with our Fast Repetition Rate Fluorometers (Behrenfeld *et al.*, 1996; Kolber *et al.*, 1990; Kolber and Falkowski, 1993; Falkowski and Kolber, 1995). This instrument can provide detailed measurements of photosynthetic parameters, that can be used to estimate photosynthetic rates in real time, as well as to provide bio-optical data for simulation models (Behrenfeld *et al.*, 1996; Kolber and Falkowski, 1993).

We propose to evaluate all of the basic variable fluorescence characteristics at sea. These measurements consist of the following:

1. Continuous sea surface mapping of variable fluorescence will be carried out by the latest bench-top version of our FRRF, equipped with solid state light sources. The precision for measurements of these parameters using the FRRF method is $\pm 5\%$ and the signal is accessible at less than $0.05 \mu\text{g}$ chlorophyll per liter. This system is used to assess the response

to nutrient limitation in real-time, to define the surface manifestation of the eddy perturbation, and to provide guidance for adaptive sampling. A previous version of this system has been used to map an eddy's effect off the coast of Hawaii (Falkowski *et al.*, 1991), and in iron-limitation experiments such as FeLine, IRONEX-I and IRONEX-II.

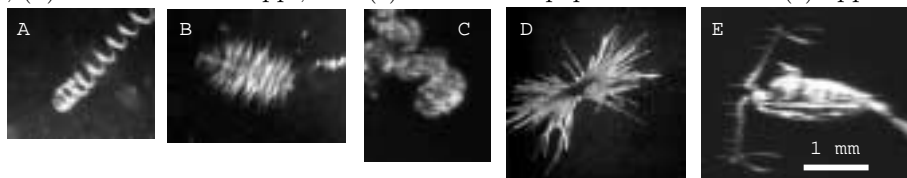
2. Vertical profiles of dark-adapted variable fluorescence parameters are critical determinates of the maximum efficiency with which light can be utilized for photosynthesis. These determinates can be used to assess the depth dependence of light or nutrient limitation and the degree and cause of photoinhibition in the near-surface waters. These measurements will be carried out with a second bench-top FRRF instrument used to assay discrete water samples collected at selected depths using the CTD rosette.
3. FRRF monitoring of on-deck incubations will be performed to evaluate the changes in photosynthetic parameters in nutrient enrichment experiments. These incubations are sometimes extremely difficult to interpret due to ill-defined "bottle" effects. FRRF measurements are independent of the chlorophyll biomass. These measurements can be interpreted in terms of the relative growth rates, allowing discrimination between the changes in the physiological efficacy, or exclusion of the grazing pressure, as a factor controlling biomass accumulation in bottle nutrient enrichments.
4. High resolution mesoscale surveys of variable fluorescence parameters will be undertaken with a dual-channel *in situ* FRRF. We plan to incorporate our submersible FRRF instrument onto the Video Plankton Recorder for this task. These data will be used to define the three dimensional structure of the eddy, and as input to algorithms that calculate instantaneous estimates photosynthetic electron transport (*i.e.* gross photosynthesis). The fluorescence parameters can be compared with measurements of radiocarbon incorporation to derive photosynthetic quotients.
5. Single-cell FRRF characterization of response to eddy pumping within different phytoplankton size classes/taxa. We developed a Single-Cell Fast Repetition Rate (SCFRR) Fluorometer to measure photosynthetic parameters of individual phytoplankton cells, and to sort cells according to size and/or fluorescence properties into one of eight compartments (Gorbunov *et al.*, 2001). The rapid measurement of the photobiological parameters on single cells permits assessment of responses of specific taxonomic groups of the phytoplankton community to the eddy disturbance. This assay will be conducted using discrete water samples collected in the biogeochemical section. The sorted cells will be collected in Eppendorf tubes for further analyses, including HPLC pigment characterizations from selected samples and microscopic examination of the cells (see *Species Composition* below).

Finally, it should be noted that direct measurement of nitrogen fixation rates are *not* proposed herein. It is our opinion that in the context of this program, such measurements could be justified only if nitrogen fixing organisms such as *Trichodesmium* are found in high enough abundance to have a significant impact on the nutrient budget. If we do find such to be the case in our first year of field work, we will propose to add nitrogen fixation rate measurements in the second field year.

6.3 Species Composition

Several overviews have emphasized the importance of eddies in controlling the structure and productivity of marine planktonic communities (Owen 1981, Angel and Fasham 1983, Mann and Lazier 1991, Olson 1991). The structure of planktonic communities, in turn, profoundly affects chemical cycling of nutrients as well as particle export and sequestration of organic material (Michaels and

Figure 6: Example images from the VPR: (a) Helical diatom chain, (b) *Chaetoceros* chain, (c) *Chaetoceros socialis* colony, (d) *Trichodesmium* spp., and (e) Calanoid copepod. Scale bar in (e) applies to all images.



Silver, 1988; Peinert *et al.* 1989; Legendre and Le Fevre, 1995; Wassman, 1998). At the mesoscale, however, there exist surprisingly little data on the structure of marine plankton communities. Notable exceptions include the Gulf Stream rings (e.g., the Ring Group, 1981; Wiebe *et al.*, 1985, 1992; Davis and Wiebe 1985; Wormuth 1985; Ducklow 1986; Hitchcock *et al.*, 1985) the California Current system (Haury, 1984; Bucklin *et al.*, 1989; Huntley *et al.*, 1995), the Eastern Australian Current (Scott 1981; Tranter *et al.*, 1983), and the Arabian and Black Seas (Piontkovski *et al.* 1995).

Our own preliminary observations and data from the Sargasso Sea lead us to hypothesize significant shifts in community structure due to eddy perturbation. During the 1997 BATS Validation Cruise 18 (described in section 6.1; see Figure 5), we observed that the abundance of the colonial cyanobacterium *Trichodesmium thebautii* and colonial radiolaria (protozoa) were notably higher within the surface waters of the eddy than outside. Sampling in this same eddy on a subsequent cruise indicated that some zooplankton, such as benthic snail larvae and larvaceans, increased in abundance by nearly an order of magnitude toward the eddy center. Other taxa, such as siphonophores, cladocera, and pteropods, were most abundant at the periphery of the eddy.

Injection of nutrients via mesoscale eddies may allow diatom blooms to occur in the Sargasso Sea. These blooms are rare events but occur periodically in the BATS time series. Somewhat surprisingly, some of the most intense diatom blooms over the last decade of BATS measurements occurred in late spring or summer, months after deep winter mixing events, indicating that nutrient input from sources other than deep winter mixing supports diatom bloom formation (Steinberg *et al.*, 2001). Bacterial production also increases significantly during these summer bloom events (Carlson, unpublished data).

We propose to compare biological populations (bacterioplankton, phytoplankton, protozoans, and mesozooplankton) within eddies and in surrounding waters to document eddy-driven changes in community structure. Sampling of planktonic community structure will be by a combination of Video Plankton Recorder (VPR) surveys, bio-optical measurements and pigment and microscopic analysis of CTD water-bottle samples.

The eddy-scale surveys shown in Figure 3 will be conducted with a towed undulating VPR. The VPR is an underwater video-microscope designed for high-resolution imaging of plankton and particles in the size range of $10\mu\text{m}$ to 10cm (Davis *et al.*, 1992a). The towed system is capable of ship speeds up to 8 knots. Images are transmitted to the ship via a fiber optic cable where they are processed and displayed in real time together with environmental variables. Calibration of the instrument with respect to the effective sampling volume facilitates quantitative estimates of absolute abundance of those organisms visible to the system. The VPR has been used extensively to measure the distributions of zooplankton and large phytoplankton over scales ranging from millimeters to hundreds of kilometers (Davis *et al.*, 1992b, 1996; Gallager *et al.*, 1996; Benfield *et al.*, 1996; Norrbin *et al.*, 1996; Sieracki *et al.*, 1998; Villareal *et al.*, 1999). If our hypothesis is correct and eddy perturbations cause a shift in species composition toward large diatoms and/or *Trichodesmium* spp., these will clearly be visible with the VPR (Figure 6).

Optical assessment of species composition by the VPR will be complemented by assays of water samples taken along the biogeochemical section (Figure 3). Specifically, phytoplankton community structure will be determined via High Performance Liquid Chromatography (HPLC) analysis of algal chlorophyll and accessory pigments from filtered CTD water bottle samples (Bidigare *et al.*, 1990; Michaels *et al.*, 1994b; Siegel *et al.*, 1990, 1995; Knap *et al.*, 1997). Analyses of the entire HPLC pigment suite will be used to partition the chlorophyll a concentration into different phytoplankton functional groups (Letelier *et al.*, 1993; Mackey *et al.*, 1996; Steinberg *et al.*, 2001). This will enable a first order assessment of changes in phytoplankton assemblage due to the eddy disturbance, as in McNeil *et al.* (1999) and Letelier *et al.* (2000).

6.4 Export

Traditionally, upper ocean particulate export fluxes have been measured using sediment traps that are suspended from a floating array. Although sediment traps have advanced our understanding of particle fluxes and remineralization more than any other tool, issues of hydrodynamic bias, swimmer contamination and particle sorting remain (see Gardner, 1996 JGOFS report for recent summary). One alternative is to use thorium-234 (half-life = 24.1 days) as a particle reactive *in situ* tracer of upper ocean fluxes. With this approach, ^{234}Th activity measurements are used to predict ^{234}Th fluxes, and these are converted to POC flux using the measured POC/ ^{234}Th ratio on particles (see summary in Buesseler, 1998). This method has also been extended to include a wider range of elemental fluxes, such as nitrogen and silicon (Buesseler *et al.*, 2001a).

Comparisons between primary production and ^{234}Th derived export flux estimates have now been made over a wide range of open ocean settings and seasons (Buesseler, 1998). The results indicate that much of the ocean is characterized by low POC export relative to primary production (^{234}Th derived export/PP \equiv *ThE* < 5-10%). Exceptions to this pattern are found during blooms at high latitudes, accompanying spring blooms at mid-latitudes, and in association with more episodic export pulses (*ThE* > 30%). Examples of the latter have been observed in the Arabian Sea in association with mesoscale processes. In particular, a cold filament upwelled at the coast and subsequently transported offshore (Brink *et al.*, 1998) produced a biological response that led to strong ^{234}Th depletion related to enhanced export (Buesseler and Benitez-Nelson, unpublished results).

There is evidence for episodic export events at the BATS site based on ^{234}Th time series (Figure 7). During the three year record available to date (Buesseler, 1998), there have been three major export events (Figure 7a). A combination of satellite altimetry and a regional hindcast model around Bermuda (see below) have been used to determine whether or not these high flux events were associated with mesoscale eddies (Sweeney, 2001). As it turns out, each of the three events took place when eddy features were present. The first two were associated with cyclonic features (negative sea level anomalies), while the last one was associated with a positive sea level anomaly. Contemporaneous hydrographic measurements reveal the latter to be associated with a Mode water eddy, a thick bolus of 18-degree water which depresses the main thermocline and lifts the seasonal thermocline. The impact of such features on upper ocean biogeochemical properties thus has the same sense as a cyclonic feature: elevated isopycnals lift nutrient-rich water into the euphotic zone, causing the accumulation of phytoplankton biomass in their interiors (McGillicuddy *et al.*, 1999). Thus the high particulate flux events inferred from thorium flux measurements appear to be consistent with eddy-driven mechanisms. However, it is clear that not every strong negative sea level anomaly is associated with high thorium flux (Figure 7b). This is not necessarily inconsistent with eddy driven upwelling, because the nature of the biological response depends on the temporal evolution of the eddy itself. For example, a decaying cyclone will actually have downwelling in its interior as the isopycnals subside to their original depths. Tracking the histories of these particular

eddies reveals that they were in fact older features (ages of four months or greater). Therefore the biological response and enhanced export are likely to have run to completion prior to the eddy's arrival at BATS (Sweeney *et al.*, submitted).

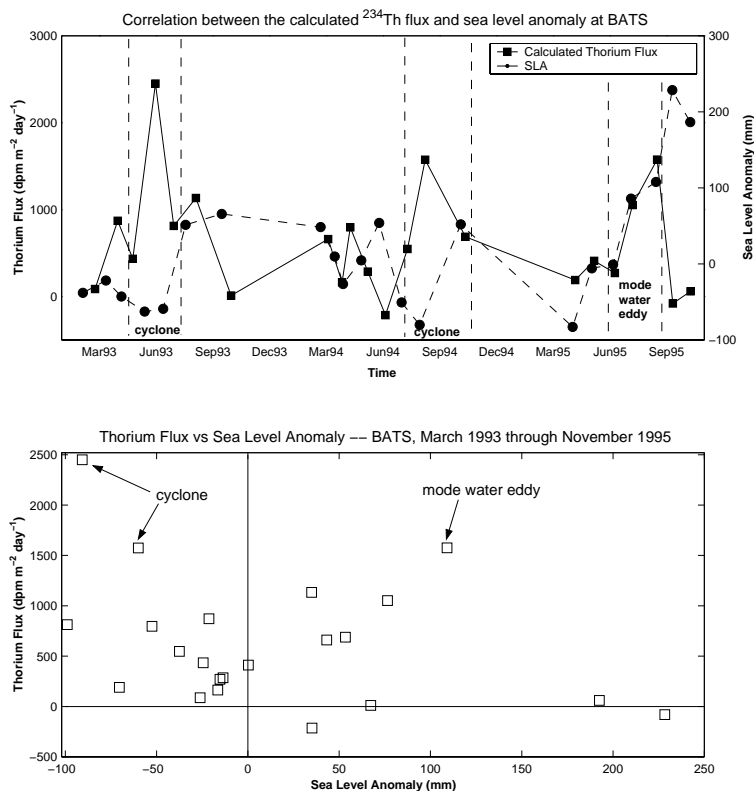


Figure 7: Top: time series of sea level anomaly and thorium-based export flux. Vertical dashed lines denote the temporal windows of the three eddy events associated with high export. Bottom: export plotted as a function of sea level anomaly.

In practice, the ^{234}Th approach requires sample collection over spatial scales appropriate to the question being posed and the temporal scale that can be quantified using the ^{234}Th tracer (days-weeks). Most often, ^{234}Th activities are lowest in surface waters and increase with depth. We will use profiles of ^{234}Th along a transect through the chosen eddies to quantify the ^{234}Th activity balance described by the following equation:

$$\frac{\partial^{234}\text{Th}}{\partial t} = \lambda(^{238}\text{U} - ^{234}\text{Th}) - P + V \quad (1)$$

where $\frac{\partial^{234}\text{Th}}{\partial t}$ is the change in ^{234}Th activity with time, ^{238}U is the uranium activity determined from salinity ($^{238}\text{U} \text{ (dpm kg}^{-1}\text{)} = 0.0686 * \text{Salinity}$), ^{234}Th is the measured activity of total ^{234}Th , λ is the decay constant for ^{234}Th ($= 0.0288 \text{ d}^{-1}$), P is the net export flux of ^{234}Th on sinking particles, and V is the sum of advective and diffusive ^{234}Th fluxes. When the ^{234}Th activity balance is integrated from the surface to a given depth, net export, P , can be calculated on a $\text{dpm m}^{-2} \text{ d}^{-1}$ basis. Repeat sampling of the eddy and surrounding waters along the biogeochemical section (Figure 3) will allow us to measure $\frac{\partial^{234}\text{Th}}{\partial t}$ directly and apply a non-steady state model to the ^{234}Th data. Samples of particulate matter obtained with *in situ* pumps will be used to quantify the elemental: ^{234}Th ratio ($\text{E}/^{234}\text{Th}$) of sinking particles. We calculate the flux of POC, PON or

biogenic silica from *P.* ($E/^{234}\text{Th}$), using $E/^{234}\text{Th}$ measured on $> 53\mu\text{m}$ particles collected below the euphotic zone (Buesseler, 1998; Buesseler *et al.*, 2001a).

For this study, we propose to apply a new procedure to measure ^{234}Th that requires only 2-4 liter water samples and minimal processing prior to beta counting at sea (Buesseler *et al.*, 2001b). We have demonstrated that the precision of our new 2 liter ^{234}Th technique is on the order of 2-3%, versus 10% or greater using prior large volume (~ 200 l) procedures. With this breakthrough in ^{234}Th analysis, we propose to collect ~ 100 ^{234}Th samples on every cruise using the standard CTD Rosette, in order to better define in space and time the ^{234}Th activity profile through the eddy using discrete samples. These data will allow us to make the most accurate flux estimates in this relatively low particle flux setting.

6.5 Biogeochemistry

Previous observations performed by the BATS program have shown distinct hydrographic and biogeochemical patterns associated with cyclonic and anticyclonic eddies (McGillicuddy *et al.*, 1999). During a survey of a cyclonic eddy in July 1997 conducted as part of BATS Validation Cruise 18, the nitracline showed a 60m uplift to a depth of $\sim 60\text{m}$ (well within the euphotic zone; Figure 5d). Several weeks later, a hydrographic and biogeochemical survey (BATS Validation 19) of the same cyclonic eddy showed uptake of nitrate from the euphotic zone and buildup of chlorophyll biomass. Upward transport of TCO_2 was observed in the upper water column of the eddy as well. The “carbocline”, a rapid increase in TCO_2 concentrations at depths of 30-50 m (analogous to the nitracline), was uplifted within the cyclonic feature and elevated TCO_2 concentrations were observed at the surface. Such surface manifestation in the biogeochemical field of inorganic carbon of the cyclonic feature has significant implications for ocean-atmospheric transfer of CO_2 (Bates, McGillicuddy and others, in preparation).

Our conceptual model of the biogeochemical impact of these eddy disturbances is as follows. Prior to the formation of the eddy, the carbocline is shallower than the 1% light level while the nitracline and phosphocline are deeper (approximately 100m and 140m, respectively). In the early stages of isopycnal doming, the carbocline rises toward the surface (thereby increasing surface TCO_2 concentrations) and the nitracline penetrates the base of the euphotic zone. The former has a direct impact on air-sea CO_2 exchange, while the latter results in uptake of nutrients, net community production, and a buildup of biomass within the euphotic zone. As the upwelling continues, the phosphocline rises into the euphotic zone as well, potentially relieving nitrogen fixing organisms from phosphorus limitation. Thus it seems likely that eddy-induced upwelling could explain the abundance of *Trichodesmium thebautii* observed in the core of the cyclonic feature sampled in BATS Validation cruises 18 and 19 (see *Species Composition* above).

It is clear from this review of the limited data in hand that the expression of these ecological responses to physical perturbation will imprint distinct biogeochemical signals on the eddy feature. These are to vary in space and evolve in time. Measurements of biological rates of production and geochemical parameters are needed to quantify the impact of eddies on these coupled biogeochemical cycles. The following parameters will be measured to assess the biogeochemical response to the uplift of isopycnals.

- Temperature, salinity, and inorganic nutrients: these will provide the physical and chemical domains of the eddy feature.
- TCO_2 , O_2 and pCO_2 : TCO_2 and dissolved oxygen will be used to determine rates of net community production within the eddy feature. Surface expression of the eddy feature in TCO_2 and pCO_2 fields will allow determination of the impact of cyclonic eddies on air-sea gas

exchange. Measurements of TCO_2 , in combination with other carbon parameters (including export) will constrain the eddy carbon budget.

- DOC: approximately 20% of new production by phytoplankton accumulates as DOC in the surface layer, so we expect this constituent to be an important component of the carbon budget in the eddy.
- DON: the nitrate that is upwelled by an eddy into the euphotic zone has three fates: non-utilization, PON export and DON accumulation. DON accumulation should represent about 20% of the net nitrate utilization. Thus it is possible that not all of the nitrate used by phytoplankton will be exported to depth; a significant fraction could be retained in the surface layer. Where nitrogen fixation is significant, DON accumulation will be in excess of that predicted from nitrate upwelling alone. The new, non-nitrate N is likely to move from the *Trichodesmium* spp. N pool to the DON pool and eventually back to the exportable N pool.
- DOP, $\delta^{15}\text{N}$ PON: Surface layer organic P concentrations in excess of that predicted from physical transport alone will be a strong indicator for operation of biological transport, perhaps in association with nitrogen fixation. Similarly, deviations in $\delta^{15}\text{N}$ of PON will indicate active nitrogen fixation within the eddy feature.

The biogeochemical response requires a complete, multi-element approach to studying the eddy. To elucidate this response, the biogeochemistry effort will include the following field measurements:

1. Core Hydrographic Measurements: CTD, discrete salinity, dissolved oxygen and inorganic nutrients ($\text{NO}_3 + \text{NO}_2$, PO_4 , SiO_4). Methods are described by Knap *et al.* (1997).
2. Core Biogeochemical Measurements: A combination of discrete and continuous measurements will be made. Discrete water column sampling includes: TCO_2 , POC/N/P, DOC/N/P, $\delta^{15}\text{N}$ PON.
3. Continuous surface measurements: underway thermosalinograph and fluorescence data, seawater and atmospheric pCO_2 ; discrete sampling of an underway stream of surface water, including TCO_2 , POM, DOM, $\delta^{15}\text{N}$ PON. Detailed method descriptions are given as follows: Hydrographic properties and POM (Knap *et al.*, 1997); DOM (Hansell and Waterhouse, 1997); TCO_2 (Bates *et al.*, 1996a); pCO_2 (Bates *et al.*, 1998c); $\delta^{15}\text{N}$ PON (Saino and Hattori, 1987).
4. Rate measurements: Primary production will be measured via dawn to dusk incubation using ^{14}C sodium bicarbonate and trace metal clean sampling techniques (Fitzwater *et al.*, 1982; Knap *et al.*, 1997).

6.6 Helium flux gauge

The processes of nutrient remineralization and return to the euphotic zone are critical elements in the long-term control of primary production in the open ocean on decade to century time-scales. However, a complete description and quantitative characterization of these important processes remains problematic. In particular, simple model formulations fall far short of predicting the fluxes of nutrients to the euphotic zone (Jenkins 1988a). High-resolution numerical models (*e.g.*, McGillicuddy and Robinson, 1997; Mahadevan and Archer, 2000) suggest that mesoscale and sub-mesoscale motions may be responsible for the upward transport of nutrients to the oligotrophic

euphotic zone. This has been supported by observation of an eddy injection event using transient tracers (Jenkins 1988b). However, such calculations are necessarily idealized, and the basic parameterization of the biogeochemical processes remains fundamentally uncertain. Furthermore, observations on the spatial and temporal scales necessary to resolve such transports represents a daunting challenge. These scales are set by the time- and space-scales associated with rapid biological uptake within the euphotic zone.

It should be possible to diagnose these processes by determining the relationship between specific tracers and biogeochemical properties. Our purpose in this survey is to characterize the relationships between a biogeochemically simple tracer, ^3He , and reactive species (nutrients, oxygen, and carbon). We propose to use these observations to define the basic nature of transport processes involved in the movement of nutrients into the euphotic zone. Ultimately, the data set created will prove an important diagnostic test of high-resolution physical-biogeochemical models.

As a tracer ^3He may be regarded as “biogeochemically simple.” That is, its behavior and boundary conditions are well-constrained within the oceanic environment. It is a stable, conservative tracer that does not undergo any biological or chemical reactions (it is a noble gas). It is technically a transient tracer, since it is produced by the radioactive decay of tritium, a bomb-fallout tracer with a 12.45 year half-life. However, the distribution of tritium in the upper subtropical North Atlantic is relatively uniform, leading to a well-constrained and straightforward *in situ* term in the ^3He conservation equation. Given present tritium concentrations in the region, ^3He may be regarded as quasi-conserved on sub-annual timescales. For example, *in situ* production accounts for only about 10% of the euphotic-zone ^3He budget (Jenkins, 1988a).

The distribution of tritiogenic ^3He in the upper kilometer of the subtropical North Atlantic strongly resembles those of the major nutrients, nitrate and phosphate. This arises because of the basic similarity between the oceanic cycles of these tracers: both ^3He and nutrients are produced within the water column below the euphotic zone. The former is created by *in situ* decay of bomb tritium. The latter are regenerated by microbial decomposition of organic material. Whereas the upper water column inventory of ^3He results from the sequestration of bomb-decayed tritium, the nutrients have accumulated from microbially mediated oxidation of organic material over similar time-scales. The net result is a strong correlation between the two tracer types. This is exemplified in Figure 8, which shows the relationship between nitrate and excess ^3He in the Sargasso Sea near Bermuda. In addition to the large-scale linear relationship between the tracers, an important feature is the deviation from the relationship in shallow waters, where the two tracers are expected to behave differently.

The mixed-layer budgets of ^3He have allowed a determination of the annual-average flux of thermocline-sequestered tritiogenic ^3He to the mixed layer/euphotic zone, and by inference (using the ^3He -nitrate relationship), the flux of nitrate into the euphotic zone (Jenkins, 1988a). Using precision long-term measurements of helium isotope ratio in the mixed-layer, one computes the requisite flux of ^3He against gas-exchange to the atmosphere. An example of such a record is shown in Figure 8, which allows the determination of the nutrient flux over annual to multiyear time-scales to the accuracy order 20-30%. The estimate thus obtained is consistent with the long-term evolution of thermocline tritium and ^3He budgets (Jenkins, 1998), and with other geochemical mass budget constraints on primary productivity (Jenkins and Wallace, 1992).

A physical-biogeochemical upper-ocean model that has predictive competence on seasonal to decadal timescales must realistically represent the processes responsible for this transport. In addition to replicating the annual-average flux of nitrate and ^3He , it must accurately represent the inter-relationships between the individual tracers (oxygen, carbon, nutrients, ^3He) and how they vary within and below the mixed layer and euphotic zone (see Figure 8). This is particularly

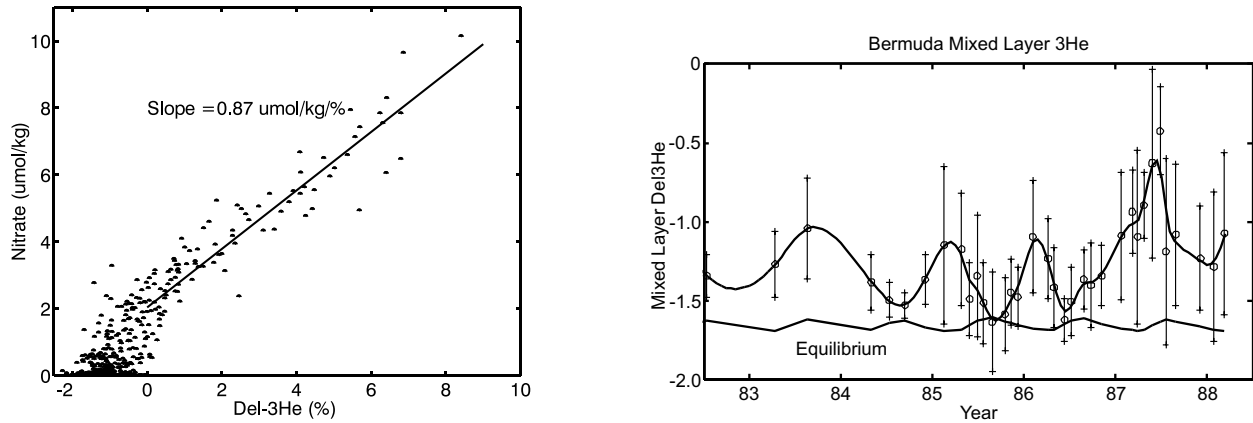


Figure 8: Left: Nitrate (in $\mu\text{mol kg}^{-1}$) versus $\delta^3\text{He}$ (per cent) in the upper thermocline and euphotic zone for several stations in the Sargasso Sea. Right: An approximately 5 year time-series of $\delta^3\text{He}$ in the mixed layer near Bermuda. Each data point is an average of several measurements, and the error bars are the standard deviation of the mean.

important, as there remains fundamental uncertainties regarding our ability to model the euphotic zone mass budgets using Redfield stoichiometry (*e.g.*, Bates *et al.*, 1996c).

Aside from the commonalities between the large-scale distributions of tritiogenic ^3He and nutrients, there are regions where the two tracers will behave differently. This deviation will be diagnostic of the processes responsible. Specifically, since the boundary conditions for ^3He are well defined and known, the non-conservative behavior of the nutrients can be quantified. Considering the action of eddy-pumping, there are four basic domains:

- In the aphotic zone, rapid remineralization of nutrients will elevate the nutrient: ^3He ratio above the thermocline/regional value. There are questions regarding the recharge of aphotic zone nutrient levels after isotherm subsidence, and this will provide constraints on the direct remineralization of nutrients that may arise from locally enhanced surface production.
- On the edges of the eddy, lateral mixing will infuse tracers onto isopycnals with their regional ^3He :nutrient ratio. Nutrient increases on isopycnal surfaces due to lateral mixing can be documented with ^3He .
- Strong diapycnal mixing zones will transport tracers in their thermocline ratio.
- In the euphotic zone, below the mixed layer, nutrients will be consumed relative to ^3He . This will be seen as a decrease in nutrient: ^3He ratio, producing a “waterfall effect” in the nutrient versus ^3He relationship (see Figure 8).
- In the mixed-layer, ^3He will be lost by gas exchange. This loss occurs at a quantifiable and predictable rate.

Thus our primary objective is to use the deviations from the thermocline relationship as a probe of these processes, and ultimately as a test of model performance. Moreover, the mixed-layer distribution and inventories of ^3He will provide an integral constraint on the upward flux of ^3He into the euphotic zone.

We propose to measure a section of profiles across the eddy during the two annual cruises (*i.e.*, along the “biogeochemical section” in Figure 3). Sampling will be concentrated between the surface

and mid-thermocline nutrient maximum. The aim will be to establish the nutrient- ^3He relationship in mixed-layer, euphotic zone, aphotic zone and thermocline, both within and on the edges of the eddy. Two hundred samples will be taken and analyzed for ^3He in each field year. To characterize the *in situ* production of this isotope, 100 samples of tritium will be measured on each of the cruises. Samples will be collected using the standard copper-tube samplers (of the style used during TTO) and extracted using established techniques. Measurement would be done at the WHOI helium isotope facility to WOCE standards ($\Delta\delta^3\text{He}$, $\leq 0.15\%$, $\Delta^3\text{H} \leq 0.5\%$, 0.02 T.U.). W.J. Jenkins will be involved in the supervision of sampling, analysis, data reduction, and interpretation.

6.7 Tracer Release

We propose to perform a tracer release experiment to measure diapycnal and isopycnal dispersion in the eddy to be studied in 2004. The release would be on an isopycnal surface whose depth is ordinarily below the nitracline but which has been lifted into the euphotic zone by the eddy. The experiment will determine the enhancement of upward transport of nutrients by diapycnal diffusion beyond that due to doming of isopycnals. It will also give a measure of the rate of homogenization within the eddy by stirring and mixing along isopycnal surfaces, and the rate of dilution of a patch of passive tracer by such mixing, both of which should apply to patches of nutrients and plankton.

Evidence is strong that diapycnal diffusivity in the upper pycnocline is normally on the order of $0.1 \text{ cm}^2/\text{s}$ (e.g., Lewis *et al.*, 1986; Gregg, 1989; Ledwell *et al.*, 1998; St. Laurent and Schmitt, 1999). Similar values have been reported from studies of penetration of SF_6 from the mixed layer into the pycnocline (Law *et al.*, 1998; A. Watson, personal communication for SOIREE), while values ten times greater were reported by Law *et al.* (2001) from another experiment of this type. A diffusivity of $0.1 \text{ cm}^2/\text{s}$ would lead to fluxes of little importance in the transport of nutrients in the present context. Hence, being sure that the diffusivity is this small would force strong constraints on theoretical and numerical models of nutrient flux: the fluxes of dissolved nutrients would have to take place along isopycnal surfaces.

On the other hand, the diapycnal diffusivity may be enhanced in anticyclonic features such as Mode-Water Eddies because of trapping of near-inertial waves (e.g., Kunze, 1985). McNeil *et al.* (1999) showed a dramatic example from the Bermuda Testbed Mooring located near the BATS site. A series of strong near-inertial waves passed by the mooring in the summer of 1995 within a Mode-Water Eddy. The gradient Richardson number, estimated from 2-point differences from instruments 26 meters apart, was apparently reduced by the inertial wave shear to values of less than 0.25 in several events during this passage (T. Dickey, personal communication). Similar events, associated with trapped near-inertial waves at anticyclonic features at a front, were reported by Granata *et al.* (1995) from the Biowatt II mooring at 34 N, 70 W in 1987. One would expect greatly enhanced mixing during these events, perhaps leading to an integrated diffusivity during the life of the eddy of $1 \text{ cm}^2/\text{s}$ or more, which would contribute to nutrient fluxes.

The methods of the tracer release experiment will be similar to those used for past experiments in the North Atlantic (Ledwell *et al.*, 1993; 1998), and in the Brazil Basin (Polzin *et al.*, 1997, Ledwell *et al.*, 2000). The release will be performed immediately after the first eddy-scale survey cruise, and the site and depth of release will be chosen on the basis of the data gathered during that cruise, on satellite data, on real-time modeling of the behavior of the eddy, and on a short CTD/XBT survey prior to the release. Three kilograms of SF_6 will be released in a 15-km streak on the target isopycnal surface, which is expected to be at a depth of 40 to 80 meters. The SF_6 must be mixed with a solvent to lower its vapor pressure below the pressure of the release. Lab experiments will be conducted to choose the solvent and test for efficient dissolution of SF_6 to insure that the tracer is not carried in bubbles or dense drops away from the target density surface. In other ways, the release will be performed as described in Ledwell *et al.*, (1998).

The early distribution of the tracer will be sampled with a towed array similar to that used for previous experiments (*ibid.*). This array includes 24 integrating samplers spaced 2 to 5 meters apart on the wire and 7 temperature sensors placed to measure vertical movements of the isopycnal surfaces relative to one another, i.e., vertical strain. The integrating samplers take in 850 ml of water over a period of ten hours while the array is towed at 0.5 m/s. Towing helps counter the horizontal streakiness of the distribution, and returns vertical profiles more efficiently than a rosette system. A sled at the center of the array carries a CTD to keep the center of the array on the target isopycnal surface. It also carries a 50-chamber sampling system, the chambers filling sequentially during the tow to find where along the tow track the tracer is encountered, with a resolution of 400 meters. At least five tows will be done, each about 20 km long. Analysis will be done on board ship with a GC/ECD system (Wanninkhof *et al.*, 1991; Law *et al.*, 1994). The transformation between height above the CTD and density will be done statistically with the aid of the temperature sensors on the wire, as described in Ledwell *et al.* (1998).

The current at the depth of the tracer release will be measured with the shipboard ADCP during the release cruise, and integrated over time, to help guide sampling. This method was used successfully in the Salt Finger Tracer Release Experiment east of Barbados at 380 meters depth in 2001 over a period of 20 days, and has also been used successfully with dye patches on the continental shelf. Three neutrally buoyant pop-up floats will be deployed along the tracer streak, timed to surface and relay their position via ARGOS early in the second tracer cruise.

On the second cruise, starting about 5 weeks after the start of the release cruise, and after the second eddy-scale survey cruise, we will sample the distribution of the tracer again with the towed system. We anticipate that the tracer streak by this time will be 40 to 100 km long, and about 10 km wide, having been elongated and curved by the motions in the eddy, and mixed in the cross-streak direction by smaller scale dispersion. At least ten 10-hour tows will be done at a speed of 1 m/s, each track being 36 km long. Each tow will be aimed to try to cross the streak at a different place. Figure 9 shows a scenario of what might happen, based on past experience.

The vertical distribution of the tracer, averaged horizontally, will start as a Gaussian curve with a second moment of less than 2 m^2 , judging from previous experiments. If the diapycnal diffusivity is independent of depth and position, then the second moment of the horizontally averaged tracer distribution will grow linearly with time with a slope of twice the diffusivity. If the diapycnal diffusivity is $0.1 \text{ cm}^2/\text{s}$ then the mean square width will grow to more than 64 m^2 after 7 weeks; if the diffusivity is $1 \text{ cm}^2/\text{s}$, it will grow to more than 670 m^2 . We will be able to obtain an accurate measure of the diffusivity in either case. Complications such as a diffusivity that depends on depth or position, and/or an incomplete survey in the presence of shear will be accounted for in a more sophisticated model of the dispersion during the analysis phase. Examples of the results to be expected can be found in Ledwell *et al.* (1998) and Ledwell *et al.* (2000).

Horizontal dispersion will also be studied with the tracer patch. A measure of the horizontal strain rate within the eddy will be obtained directly from the growth of the length of the tracer streak. We hope to measure this length from a complete survey, but it can also be estimated from concentrations found in a partial survey. This strain rate can be used to characterize stirring within the eddy at scales of 10 to 100 km. The width of the streak, in combination with the strain rate, will give an estimate of the lateral diffusivity at scales of 1 to 10 km, as in Ledwell *et al.* (1998). This diffusivity will be useful in quantifying the mixing of patches of nutrients and plankton with their surroundings at those scales.

It is important to try to characterize the forcing of the diapycnal mixing in order to generalize the results of the tracer release experiment. Energy for diapycnal mixing in the present case comes from vertical shear. We shall measure the shear at 8-meter x 2-minute resolution with a shipboard

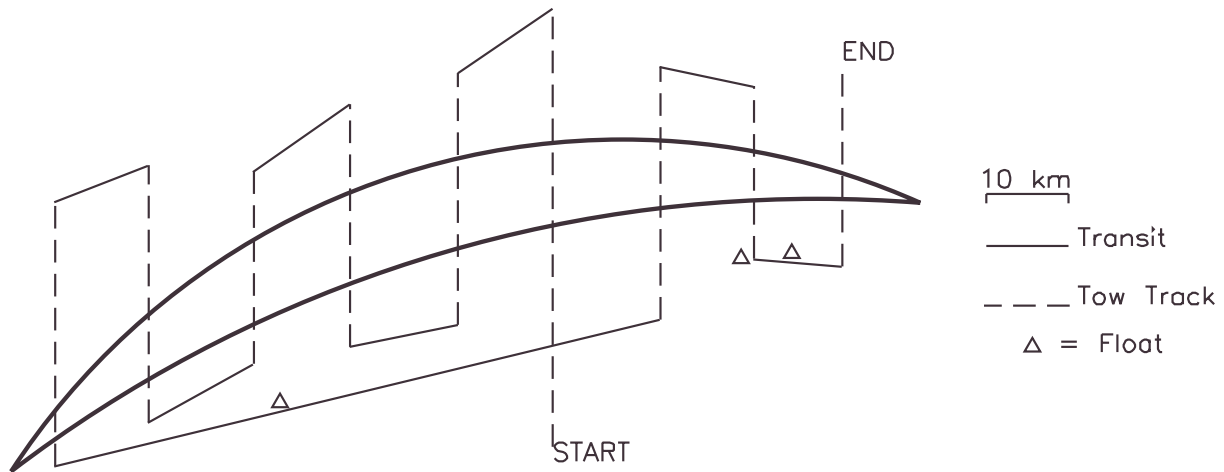


Figure 9: Scenario for the final tracer sampling survey. The 100-km length of a hypothetical banana-shaped tracer streak (bold line) would result only if the release were toward the edge of the eddy rather than near the center, as intended. The pop-up floats (triangles) are off by 10 to 20 km, and two of them have come together. Misguided a little by the floats, we start too far to the south of the streak and must do a second 40-km tow (dashed lines) along the same line as the first to find the streak, or to cross all of it. Then we systematically work our way west with tows parallel to the first, always underestimating the bend because of a lag of several hours between sampling and analysis. When concentrations become low in the west, we jump to the east and do the remainder of the ten tows, not quite reaching either end of the streak. Despite the difficulties, a good survey is obtained.

ADCP, both during the tracer cruises and the eddy-scale survey cruises. The 10-meter shear, scaled with the stratification, has been proposed as an estimator for diapycnal mixing by Gregg (1989), and has since then often been used to characterize the energy available for mixing in the open-ocean internal wave field. The ship will be on site for more than half of the duration of the tracer experiment, so that ample shear statistics will be gathered. The array of temperature sensors in our towed system, and the towed body during the eddy-scale surveys will enable us to measure strain statistics in the depth range of interest for several hundred hours. These will be used with the shear data to test for anomalies in the internal wave field, which might influence interpretation of the 10-meter shear. They will also be used to make rough estimates of gradient Richardson number on the scales accessible with the ADCP.

It would be advantageous to measure fine structure accurately for the duration of the tracer experiment, especially to estimate Richardson number and overturn scales. Instruments to do this are being developed by John Toole at WHOI and Sally McIntyre at UCSB. Both have expressed an interest in using the present experiment as a pilot study for their instruments, and may propose to do so in time to join the experiment.

6.8 Modeling and Synthesis

Numerical modeling will play an important role in the execution of our experimental work at sea, as well as subsequent interpretation of the observations. A variety of modeling approaches have been brought to bear on mesoscale biogeochemical processes in the Sargasso Sea, including (1) process-oriented simulations (McGillicuddy and Robinson, 1997), (2) data-assimilative forecasting and hindcasting (McGillicuddy *et al.*, 1999), and (3) satellite-based statistical models (Siegel *et al.*, 1999). As part of a NASA-funded JGOFS SMP project, the coupled quasi-geostrophic and surface boundary layer model used in (1) and (2) has been configured in the “Topex/Poseidon Diamond” surrounding the BATS site (McGillicuddy and Kosnyrev, 2001). This

implementation makes it possible to prescribe the necessary physical model boundary conditions directly from T/P altimetry (Figure 10). Results are available in animated form on the web at <http://science.whoi.edu/users/mcgillic/tpd/anim.html>. We expect to use a mixture of these approaches for staging the experiment, optimizing our sampling deployment using nowcasts and forecasts, and interpreting the results with hindcast simulations. In particular, the latter will involve incorporating fully coupled biological and biogeochemical components into these three-dimensional circulation models.

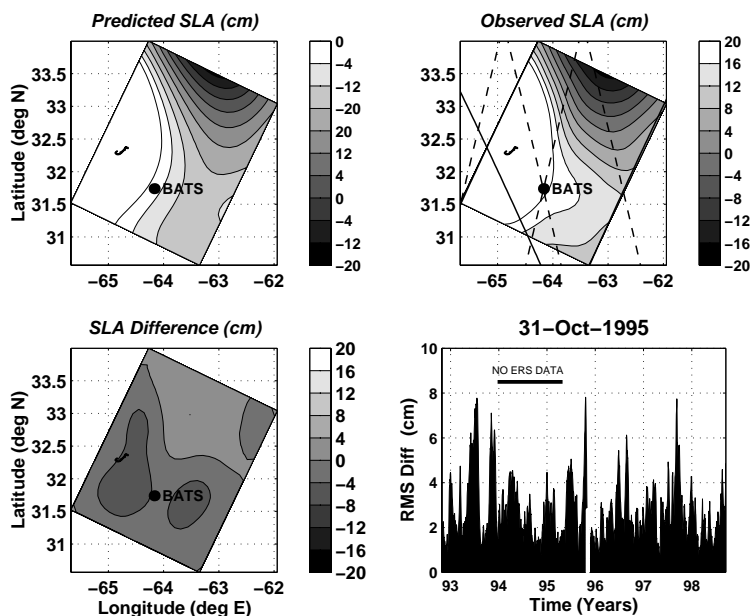


Figure 10: An example snapshot of model output (31 October 1995) from the central hindcast. Upper left: predicted SLA; upper right: objectively analyzed SLA (solid and dashed lines show T/P and ERS ground tracks, respectively); lower left: difference between simulated and observed SLA; lower right: time series of RMS difference between simulated and observed SLA averaged over the model interior (white vertical bar indicates the time of this particular snapshot).

Until very recently, mesoscale phenomenology was not accessible in large-scale ocean models—eddy resolving simulations were only possible in regional contexts. Increased computational capability, together with progress in ocean modeling, have facilitated some of the first truly eddy resolving basin-scale simulations (*e.g.* Smith *et al.*, 2000). As part of an NSF-funded project within JGOFS SMP, we have incorporated an idealized nutrient transport model into a 0.1 degree resolution simulation of the North Atlantic, using the Los Alamos Parallel Ocean Program (Figure 11). Diagnosis of the model solutions suggests that, except for the wintertime period of deep convection, the dominant mechanism of nutrient input to the euphotic zone is vertical advection by eddies. Annual fluxes in the Sargasso Sea are of the same order as the regional estimates mentioned above. Although these results are consistent with the notion that eddies play an important role in nutrient transport to the upper ocean, they do not explicitly represent the complex biological regulation of their impacts on biogeochemical cycling. Furthermore, our simulations to date have not been of sufficient duration to examine the role of eddies in maintaining the background biogeochemical state. We propose to incorporate what is learned in our field work about the nature of these controls into this model to investigate their implications with respect to large-scale elemental cycling in the ocean. Clearly we must move beyond simplified formulations with aggregate repre-

sentations of nutrients, phytoplankton and zooplankton (so-called “N-P-Z” models). The concept of functional groups has shown some promise in that regard (*e.g.*, Hood *et al.*, 2001).

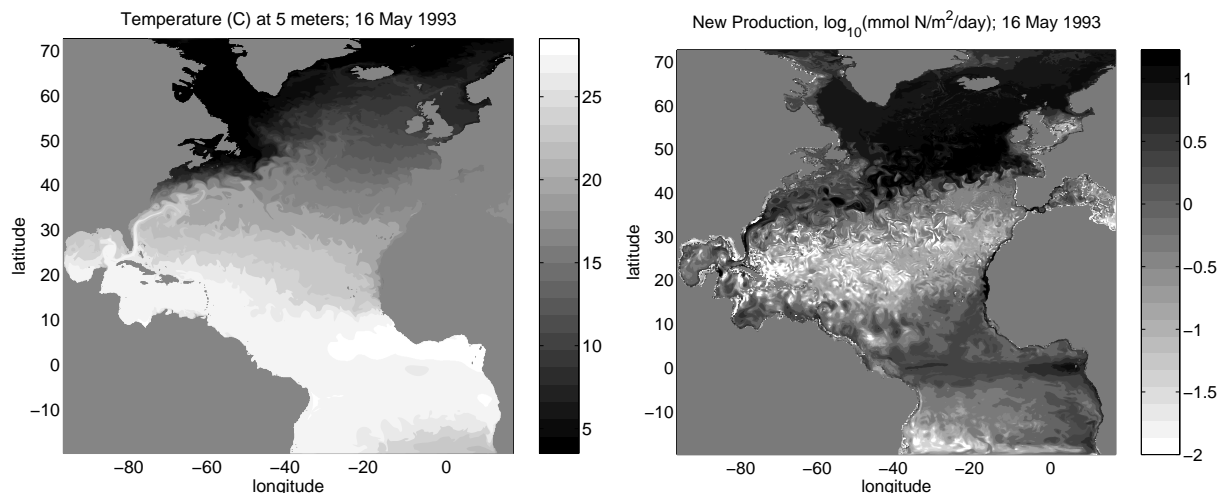


Figure 11: Snapshots of temperature and new production in a 0.1° simulation of the North Atlantic.

In addition to these dynamical models, we also propose to use satellite-based kinematic and statistical approaches to investigate the effects mesoscale eddies on basin-scale biogeochemical cycles. That is, field observations will be used in conjunction with satellite data to make basin-scale estimates of biogeochemical rates due to mesoscale features. This will follow the approach used by Siegel *et al.* (1999) where hydrographic data from monthly BATS sampling and satellite altimetry observations were used together to make regional scale estimates of the new production due to eddies. Here, we propose to couple that analysis of vertical advection and nutrient uptake to include explicitly the processes of nutrient remineralization and isopycnal and diapycnal mixing. Required data for this task will be sampled as part of the proposed field program. These results will provide data-driven estimates of the eddy pumping flux of nutrients and their role in basin-scale biological and biogeochemical processes.

7. Broader Impacts

The research effort outlined above provides an excellent context in which to conduct a number of educational and outreach activities. Our main thrust in all of these will be to communicate the necessity of integrated approaches to complex interdisciplinary problems in the ocean. Paralleling our research component, this activity will emphasize the synergy between theory, observation, modeling, and remote sensing. Our specific objectives are threefold:

1. Participation of graduate students in the proposed research activity.

We have a three-pronged approach to facilitate graduate student participation in our program. First, the budget includes some direct support for graduate research assistance. Second, we intend to entrain students currently enrolled at our home institutions with fellowship support. Finally, we will endeavor to recruit additional students to our institutions to work on the project, again under extramural fellowship support. We feel that this is a realistic possibility given the four-year duration of the project.

2. Curricular development.

Several of the PIs (Bates, Falkowski, Hansell, Jenkins, Siegel) are actively involved in teaching graduate (and some undergraduate) level courses at our home institutions. We intend to take this opportunity to expand our curriculum in the general subject of complex physical–biological–biogeochemical interactions in the ocean. Furthermore, we are beginning to expand the scope of our educational activities beyond the traditional learning environments. In particular, WHOI has begun a major effort to establish an on-line learning infrastructure as part of the FATHOM partnership (<http://www.fathom.com>). We propose to develop content for this site that documents what we learn in our research program.

3. Web-based outreach.

We propose to develop a centralized website at WHOI for transmitting our results to the scientific community and will work with our institutional outreach sites to provide greater exposure in the K-12 and public contexts. All of the institutions involved with this work (WHOI, Rutgers, UCSB, RSMAS and BBSR) all have active web-based outreach programs that seek content from scientific programs. We plan to work with our institutional outreach programs to provide real-time webcasts of cruise activities. This has proven to be a very exciting way of engaging K-12 students as was done in the U.S. JGOFS Southern Ocean, as well as the JASON and Sustainable Seas expeditions. The students will see how the investigators use remote sensing and other data to find an eddy at sea and how the detailed distributions of biological and chemical properties are mapped out.

8. Significance

The question of nutrient supply for new production in the subtropics has been problematic for two decades. Over the last few years, new evidence has emerged to suggest that intermittent nutrient injection events associated with mesoscale eddies could reconcile this issue. However, key questions remain with respect to upper ocean mixing, biological rates, species composition, export and impacts on coupled biogeochemical cycles. The proposed field program will provide a detailed characterization of the biological and chemical ramifications and feedbacks that result from these physical disturbances. Such information will allow us to test the hypothesis that eddy-induced nutrient supply increases gross photosynthesis, changes community structure, and thereby increases export.

In a broader context, this system provides us with a natural perturbation experiment in which the linkages between the physical environment, the biota and biogeochemical cycling can be studied. Knowledge of these complex interactions is essential if we are to come to a syntheical understanding of how the modern ocean works from a global perspective. Progress in this area could provide critical information about how the ocean has responded to environmental changes in the past, and how it might do so in the future.

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