<u>Project Summary</u>

Coupled physical–biogeochemical models provide a useful framework for testing our ideas about the underlying physical, biological and chemical controls on elemental cycling in the ocean. Up to now, efforts to do so on the scale of ocean basins have produced mixed results. The seminal work of Sarmiento *et al.* (1993) and Fasham *et al.* (1993) demonstrated that the large scale distributions of chlorophyll in the surface waters of the North Atlantic could be simulated with a reasonable degree of accuracy using a simple planktonic ecosystem embedded in a coarse resolution general circulation model. While the general characteristics of these large scale patterns were consistent with observations, detailed comparisons with time series data at specific sites revealed that the underlying flux balances maintaining these distributions were not as satisfactory.

During the last several years, there has been significant progress in the development of more realistic general circulation models. Areas of improvement particularly relevant to biogeochemical processes include (1) aspects of the time-mean flow, (2) treatment of the surface boundary layer, and (3) the resolution of mesoscale eddies. This next generation of GCMs represents a substantial step forward in the physical bases on which coupled biogeochemical simulations can be built. It is proposed herein to conduct basin scale eddy-resolving biogeochemical simulations of the North Atlantic to examine the impact of mesoscale processes on large scale elemental budgets.

Our prior results have demonstrated a dramatic shift in the phenomenology of nutrient transport as resolution is increased from coarse scales (1.6 degrees) to the eddy resolving case (0.1 degrees). Whereas coarse resolution models suggest the dominance of convective and diffusive nutrient supply, eddy-induced upwelling plays an important role in the high resolution calculations. In 1999 we were very fortunate to have the opportunity to participate in a pilot high-resolution (0.1 degree) simulation at LANL, carried out by M. Maltrud. 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 those derived from regional eddy-resolving models (McGillicuddy, et al., 1998; McGillicuddy and Robinson, 1997) and satellite-based estimates of new production (Siegel *et al.*, 1999).

A suite of experiments is planned with a five-component biogeochemical model (the OCMIP-2 formulation) run at resolutions of 1.6 degree (coarse), 0.4 degree (eddy-permitting) and 0.1 degree (eddy-resolving). The coarse resolution runs will be used as a benchmark for comparison with other such models, and serve as a control run for the higher resolution calculations. Although the eddy-permitting case will most likely not be entirely sufficient for a comprehensive study of mesoscale processes, it does represent a meaningful intermediate step that will provide useful information without incurring the substantial computational cost of the 0.1 degree runs. This will set the stage for a relatively small number of fully eddy-resolving runs which have only recently become feasible from a computational point of view. Understanding gained from these experiments will be used to guide the development of parameterizations for mesoscale biogeochemical processes to permit their inclusion in larger scale (global) models.

Results of Prior NSF Support

D.J. McGillicuddy, Jr.: The Role of Eddies in Basin Scale Biogeochemical Budgets of the North Atlantic (OCE-9725974, 1/1/98-12/31/00).

Funding from this grant helped support a variety of investigations of the impact of mesoscale eddies on biogeochemical cycling in the ocean. McGillicuddy *et al.* (1998) presented four lines of evidence which suggested eddy-induced nutrient transport could be sufficient to balance geochemical estimates of new production in the Sargasso Sea: regional numerical simulations, satellite-based flux estimates, mesoscale biogeochemical surveys, and high temporal resolution moored time series. These latter three topics[1] were followed up with more detailed treatment in Siegel *et al.* (1999), McGillicuddy *et al.* (1999) and McNeil *et al.* (1999). Subsequently, McGillicuddy *et al.* (in press) documented covariation in satellite-derived ocean color and sea surface temperature measurements which are phenomenologically and statistically consistent with eddy-driven upwelling. Three review papers (Flierl and McGillicuddy, submitted; Garcon *et al.*, submitted; McGillicuddy, submitted) deal with various aspects of mesoscale physical-biogeochemical interactions. Finally, it is worth noting that a manuscript describing a basin scale eddy-resolving nutrient transport simulation is in preparation; highlights of the results are presented in the project description below.

<u>Refereed publications supported in full or in part by this award:</u>

McGillicuddy, D.J., Robinson, A.R., Siegel, D.A., Jannasch, H.W., Johnson, R., Dickey, T.D., McNeil, J., Michaels, A.F. and A.H. Knap, 1998. Influence of mesoscale eddies on new production in the Sargasso Sea. *Nature* **394**:263-265.

McGillicuddy, D.J., Johnson, R.J. Siegel, D.A., Michaels, A.F., Bates, N.R. and A.H. Knap, 1999. Mesoscale variations of biogeochemical properties in the Sargasso Sea. *Journal of Geophysical Research* **104**(C6): 13,381-13,394.

Siegel, D.A., McGillicuddy, D.J. and E.A. Fields, 1999. Mesoscale eddies, satellite altimetry and new production in the Sargasso Sea. *Journal of Geophysical Research* **104**(C6):13,359-13,379.

McNeil, J.D., Jannasch, H.W., Dickey, T.D., McGillicuddy, D.J., Brzezinski, M. and C.M. Sakamoto, 1999. New chemical, bio-optical and physical observations of upper ocean response to the passage of a mesoscale eddy off Bermuda. *Journal of Geophysical Research* **104**(C7): 15,537-15,548.

McGillicuddy, D.J., Kosnyrev, V.K., Ryan, J.P. and J.A. Yoder. Covariation of mesoscale ocean color and sea surface temperature patterns in the Sargasso Sea. In press, *Deep-Sea Research II*, special volume on HOT/BATS.

Flierl, G.R. and D.J. McGillicuddy. Mesoscale and submesoscale physical-biological interactions. Submitted, *The Sea*.

Garcon, V.C., Oschlies, A., Doney, S.C., McGillicuddy, D.J. and J. Waniek. The role of mesoscale variability on plankton dynamics. Submitted, *Deep-Sea Research II*, special volume on JGOFS North Atlantic Synthesis.

McGillicuddy, D.J. Models of small-scale patchiness. Submitted, *Encyclopedia of Ocean Science*.

[1]Note that the regional modeling study (McGillicuddy and Robinson, 1997) was published prior to this award.

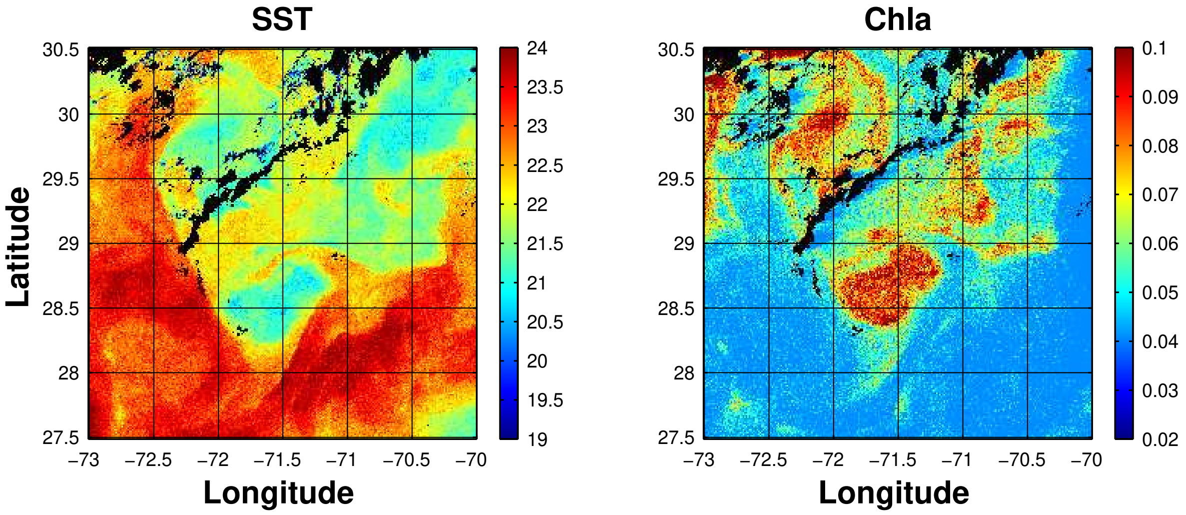
Impacts of mesoscale processes on biogeochemical fluxes in the North Atlantic: basin-scale eddy-resolving simulations.

1. Introduction

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 mol N m^{-2} 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, 1998a). 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.*, 1994). Modern estimates of mixing rates in the thermocline (Lewis *et al.*, 1986; Ledwell *et al.*, 1993; Ledwell *et al.*, 1997) 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, 1997). 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; Falkowski *et al.*, 1991). 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 magnitude sufficient 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). Mesoscale biogeochemical surveys carried out as part of the BATS Validation activities have documented the impact of 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.*, 1999a). Similar patterns emerge from an analysis of satellite-derived sea-surface temperature and pigment fields (McGillicuddy *et al.*, in press). 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 1). This covariation in property distributions demonstrates the impact of the eddies extends all the way to the surface.

Figure 1: Simultaneous images of AVHRR sea surface temperature (°C) and and CZCS-derived pigment biomass (mg Chl m^{-3}) in the Sargasso Sea on April 20, 1984.



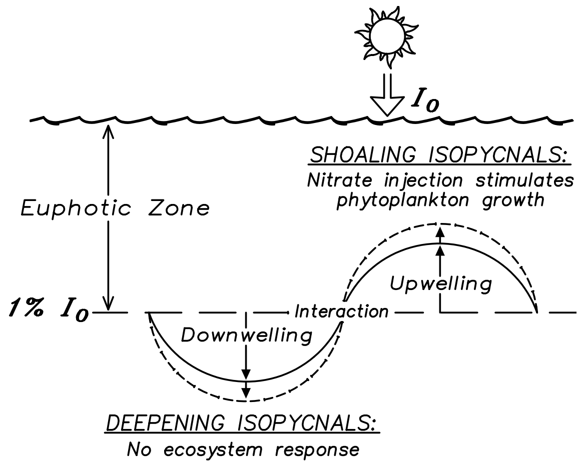


Figure 2: A schematic representation of the eddy upwelling mechanism. The solid line depicts the vertical deflection of an individual isopycnal caused by the presence of two adjacent eddies of opposite sign. The dashed line indicates how the isopycnal might be subsequently perturbed by interaction of the two eddies.

The eddy upwelling mechanism can be conceptualized by considering a density surface with mean depth coincident with the base of the euphotic zone (Figure 2). 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.

2. Previous Work on Basin Scale Biogeochemical Modeling in the North Atlantic: Successes and Shortcomings

The seminal work of Sarmiento *et al.* (1993) and Fasham *et al.* (1993) documented the first substantial effort to use a planktonic ecosystem model embedded in a general circulation model (GCM) to investigate the physical-biological interactions which impact basin scale biogeochemical budgets in the North Atlantic. Their general approach was to incorporate Fasham *et al.*'s (1990) seven compartment nitrogen-based biological formulation into a relatively coarse resolution (2°) primitive equation circulation model. Under climatological forcing conditions, the coupled model was run out to a quasi-steady statistical equilibrium and the underlying controls were diagnosed. Subsequent work has included a parameter dependence and sensitivity analysis of these numerical solutions conducted by Slater *et al.* (1993), and some initial experiments involving assimilation of satellite-derived chlorophyll distributions (Armstrong *et al.*, 1995). Oschlies and Garcon (1999) and Oschlies *et al.* (2000) used a simpler four-compartment NPZD ecosystem model in an eddy-permitting (1/3 °) resolution model of the North Atlantic. Dutkiewicz *et al.* (in press) examine interannual variations in basin-scale chlorophyll patterns using a simple ecosystem in a coarse resolution GCM.

Detailed comparisons of these simulations to observations has revealed mixed results. One aspect in which the model solutions agree particularly well with data is the large scale chlorophyll distribution (Sarmiento *et al.*, 1993); Oschlies *et al.*, 2000). The overall pattern in the annual mean concentration is quite similar to satellite-based estimates from CZCS, including low pigment in the main subtropical gyres, and higher concentrations in upwelling regions and the subpolar gyre. Furthermore, the modeled seasonal variations about the annual mean also compare favorably with observations (not shown). Given the fact that such simulations were constructed using a fixed set of ecosystem parameters over the entire domain, this agreement is especially intriguing.

Although such models capture the general characteristics of the seasonal changes in surface chlorophyll, comparison with time series data at fixed points reveals significant problems. For example, wintertime nitrate concentrations at Station S exceed observed values by up to an order of magnitude (Fasham *et al.*, 1993; Oschlies *et al.*, 2000). The vertical structure of the simulated distribution is also suspect, in that the nitracline is much shallower and sharper than is observed. Simulated phytoplankton concentrations tend to be too high (low) in the spring (summer). These systematic errors tend to compensate for each other in terms of annual primary production, producing the "right" answer for the "wrong" reasons: over(under)estimation during the bloom(oligotrophic) periods.

Analysis of the annual nutrient budgets near Bermuda (Table 1) reveals even more troublesome issues. In the Fasham *et al.* (1993) analysis, nitrate supply is dominated by horizontal advection, mostly in the meridional direction. Convection is the next largest contribution to the annual budget, but nearly one half of the convective input is counterbalanced by downwelling driven by Ekman convergence (the vertical advection term). Diffusion plays only a minor role, and the balance of terms yields an annual new production which is within the range of geochemical estimates (0.50 ± 0.14 mol N m^{-2} yr^{-1}). In contrast, the eddy-permitting simulation of Oschlies *et al.* (2000) suggests far less lateral input of nitrate in this region. The annual new production of 0.66 mol N m^{-2} yr^{-1} is at the upper limit of observational estimates, and is almost entirely driven by vertical mixing (Oschlies *et al.* do not distinguish between convection and diffusion in their model). Interestingly, both the coarse resolution and eddy permitting simulations predict similar fluxes due to vertical advection (net transport out of the euphotic zone). Both are forced with monthly climatological winds from Hellerman and Rosenstein (1983), so the Ekman downwelling driven by wind stress curl is likely comparable in the two models. Assuming that the bulk fluxes of nitrate are not sensitive to differences in the biogeochemical models, it can be inferred that eddy activity in the Oschlies *et al.* model does not contribute significantly to new production near Bermuda. A high-resolution (0.1°) eddy resolving simulation of the North Atlantic (see below) suggests that vertical transport associated with mesoscale features is sufficiently strong to overcome Ekman downwelling in this region, causing vertical advection to be a net source of nitrate in this region (Table 1).

	Fasham *et al.* (1993) 2.0° (coarse res.)	Oschlies *et al.* (2000) 0.3° (eddy permitting)	This study 0.1° (eddy resolving)
Horizontal transport	0.38	0.10	0.07
Vertical advection	-0.16	-0.13	0.13
Vertical mixing	0.35	0.66	0.58
convection	0.34	–	0.46
diffusion	0.01	–	0.12
Annual New Production	0.57	0.63	0.34

Table 1: Nitrate budgets and annual new production (both in mol N m^{-2} yr^{-1}) in three different models (see text). Note that Oschlies *et al.* (2000) do not distinguish between convection and diffusion in the vertical mixing term. Geochemical estimates in this region suggest an annual new production of 0.50 ± 0.14 mol N m^{-2} yr^{-1} (see Table 3).

To summarize, three different models suggest three different scenarios for how the nitrogen cycle works in the Sargasso Sea. The coarse-resolution simulations of Sarmiento *et al.* (1993) and Fasham *et al.* (1993) suggest the primary source of nitrate is through horizontal advection; in the eddy-permitting case of Oschlies *et al.* (2000) it is vertical mixing; in the present eddy-resolving case, eddy-driven vertical fluxes are sufficient to overcome mean wind-forced downwelling to make vertical advection a net source of nitrate. How can these different views of the nitrogen cycle be reconciled?

Although differences in the biogeochemical formulations of the three models cannot be dismissed, the fact that nitrate supply to the upper ocean is a physically-driven process points toward more detailed scrutiny of the differences in physical frameworks used to drive the simulations. For example, the large horizontal flux of nitrogen into the Sargasso Sea in the Sarmiento *et al.* (1993) and Fasham *et al.* (1993) simulations may be related to the impact of the mixing parameterization used at this relatively coarse resolution. In a careful analysis of the heat transport in GCMs, Böning *et al.* (1995) documented the presence of strong upwelling inshore of the Gulf Stream which significantly impacts structure of the simulated thermohaline circulation. The underlying causes of this aspect of the numerical solutions relate to the behavior of the mixing parameterization (which is typically applied on level surfaces in z-coordinate models) in the presence of strongly sloping isopycnals, as in the case of the western boundary current. This problem can be controlled to some degree by increased resolution and commensurate decrease in the coefficients of horizontal diffusion. This may explain the much reduced role of horizontal nitrate transport in the Oschlies *et al.* (2000) eddy permitting simulation and the eddy-resolving case described herein (Table 1).

3. An eddy-resolving simulation of the North Atlantic

3.1 Physical model

The coupled physical-biogeochemical model is based on the Los Alamos Parallel Ocean Program (POP) (Smith *et al.*, 1992). It is a level-coordinate model that solves the three-dimensional primitive equations with a free surface and realistic bottom topography. Essentially it is an implementation of primitive equation ocean dynamics described in Bryan (1969), with a number of important numerical improvements. In addition, it has been adapted to run efficiently on massively parallel computational architectures.

The model domain extends from 20°S in the South Atlantic to 72.6°N in the North Atlantic, and from 98°W to 17.2°E (Figure 3). It includes the Gulf of Mexico and the western Mediterranean Sea, but excludes Hudson Bay. The computational mesh consists of a Mercator grid with a resolution of $\Delta\lambda = 0.1^\circ$ and $\Delta\phi = 0.1^\circ \cos\phi$ where λ and ϕ are longitude and latitude, respectively. The horizontal resolution varies from 11.1km at the equator to 3.2km at the northern boundary, such that the grid spacing is everywhere less than or equal to the zonal-mean Rossby radius of deformation. The vertical grid consists of 40 non-uniformly spaced levels, distributed in a Gaussian function of depth. Level thicknesses vary from approximately 10m at the surface to 250m at mid-depth. Bathymetry was derived from the $\frac{1}{12}^\circ$ resolution ETOPO5 database from the National Geophysical Data center.

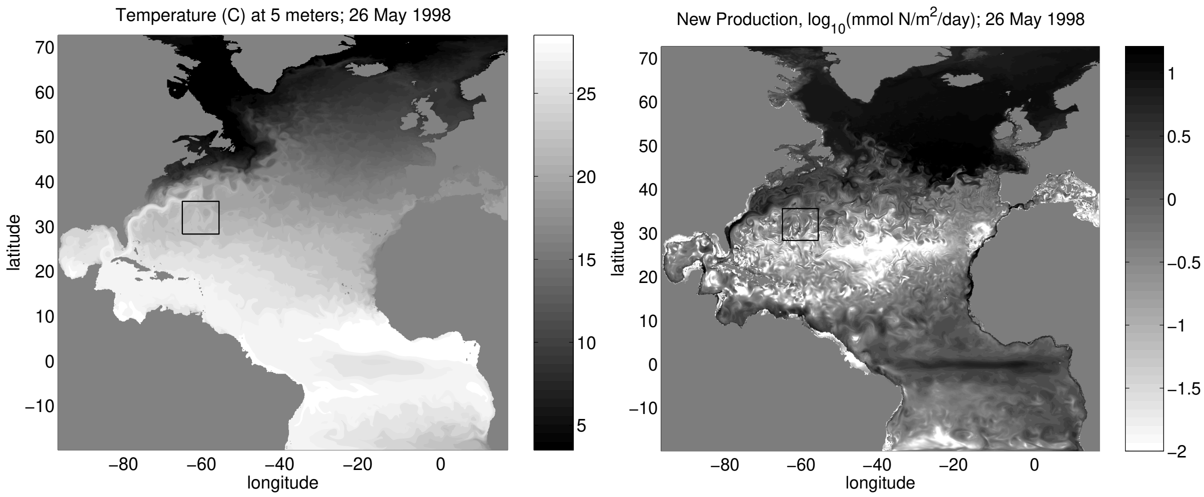


Figure 3: Snapshots of temperature and new production in a 0.1^circ degree simulation of the North Atlantic.

Subgridscale horizontal mixing processes are parameterized with a biharmonic operator. Viscosity and diffusivity vary with the cube of the grid spacing, using values that are as small as possible yet still maintain computational stability. Vertical viscosities and diffusivities are computed based on the Richardson number formulation described by Pacanowski and Philander (1981) with background values of 10^{-4} and 10^{-5} m^2 s^{-1}, respectively. In addition to this explicit integration of the vertical mixing terms, two passes of a standard convective adjustment scheme are made each time step. A quadratic bottom stress is applied at the ocean bottom.

The model ocean is initialized at rest, with temperature and salinity values set to their climatological values for June in the Levitus (1982) climatology. Surface forcing consists of six-hourly ECMWF surface analyses with surface heat fluxes prescribed from the Barnier *et al.* (1995) seasonal climatology. Freshwater fluxes are simulated by restoring surface salinity to daily interpolations of the Levitus (1982) monthly climatology. There are 3°-wide buffer zones at the northern, eastern and southern boundaries in which temperature and salinity are also restored to the Levitus climatology with a time scale that varies linearly from zero at the boundary to 15 days at the edge of the buffer.

The physical model is spun up for a period of 15 years during which it reaches a state of quasi-equilibrium. Kinetic energy reaches stationarity in 2-3 years, which is a typical time scale for baroclinic adjustment of the velocity field to an initial density distribution. Volume-averaged temperature approaches a steady annual cycle after approximately ten years. Although these integrated statistics suggest that the initial phase of rapid adjustment to initial conditions is complete, there is a much longer time scale (on the order of the turnover time for the entire basin) for the model to achieve true equilibrium. Current computational capabilities do not permit integrations of such duration.

See Smith *et al.* (2000) for a detailed description of the 0.1° simulation on which the coupled model is based.

3.2 An idealized nutrient transport model

In order to ascertain the impact of various circulation processes on nutrient transport to the upper ocean, an idealized one-tracer model representing nitrate was incorporated into the physical model described above. In this model, the water column is partitioned into a euphotic zone (above 100m) where biological uptake of nitrate occurs and an aphotic zone (below 100m) where nitrate is restored to its observed concentration as a function of density via a first-order reaction. Nitrate uptake by phytoplankton is assumed to take the form

$$\text{uptake rate} = \mu \min(Q, L)$$

where the temperature-dependent maximal uptake rate μ is modulated by non-dimensional light and nutrient limitation factors via Liebig's Law of the Minimum (Liebig, 1845; Kiefer and Mitchell, 1983; Hurtt and Armstrong, 1996). Nutrient limitation Q is expressed in Michaelis-Menten form, whereas light limitation is formulated as an exponential function characteristic of traditional photosynthesis versus irradiance relationships (*e.g.* Platt *et al.*, 1980), although effects of photoinhibition are neglected:

$$Q = N/(k_n + N) \qquad L = 1 - \exp(-\alpha I)$$

The temperature dependence of the maximal rate is given by Eppley's (1972) formula $\mu = \mu_0 1.884^{(T-20)/10}$. Photosynthetically available radiation (I) is assumed to be 45% of the shortwave flux specified in the Barnier *et al.* (1995) seasonal climatology. A constant extinction coefficient of 0.044 m^{-1} is used to compute the underwater light field. See Table 2 for a list of model parameter definitions and values.

Remineralization of nitrate in the aphotic zone is parameterized as a first-order relaxation to observations with time scale τ:

$$\text{remineralization rate} = \tau(NO_3^*(i,j,\sigma_\theta^*) - NO_3)$$

where $NO_3^*(i,j,\sigma_\theta)$ is interpolated from a three-dimensional lookup table in which every (i,j) grid point in the model has a nitrate–density relationship based on the nitrate field from the NODC World Ocean Atlas 1998 (WOA98). The reference density field σ_θ^* is an average of the simulated density from the final two years of the spinup period. Use of the model-derived density reference is necessary because of the slow drift of the simulated density away from the initial conditions during the integration.

μ_0	maximum new production rate	0.5 mmol N m^{-3} d^{-1}
k_n	half-saturation constant for nitrate limitation	0.1 mmol N m^{-3}
α	initial slope of light response	0.05 m^2 W^{-1}
τ	nitrate restoring time scale	0.1 d^{-1}

Table 2: Parameters of the nutrient transport model.

Density is a natural coordinate for referencing the nitrate field in this investigation, as eddy-induced nutrient transport mechanism of interest here is a result of vertical isopycnal displacements. The underlying assumption of this model is that the nitrate–density relationship below the euphotic zone is restored on time scales comparable to or shorter than the period of the vertical displacements associated with the supply events. Let us examine this assumption by considering a fluid parcel caught in an upwelling event. As the parcel rises into the euphotic zone, nitrate is removed by photosynthesis. As the parcel is subsequently downwelled into the aphotic zone, it is re-fortified with nitrate which is remineralized during processes which occur in association with the decay of sinking particulate material. Thus, it will bring new nitrate with it the next time it is upwelled. If the period of the vertical displacements were fast compared to this restoring time scale, such a model would tend to overpredict the upward flux of new nitrate. However, such does not appear to be the case. Because the bulk of the nutrient transport associated with mesoscale eddies is associated with upwelling in their interiors during eddy formation and intensification, the time scale most relevant to such nutrient injections is that of an eddy lifetime (McGillicuddy and Robinson, 1997). Typical mid-ocean eddies last for six months, with some lagrangian drifter observations suggesting persistence of individual features for up to 430 days (see review by Richardson, 1993). Given that an upwelled fluid parcel will be, statistically speaking, downwelled in the next dynamical event in which it participates, it can be argued that the nominal period of vertical displacements is on the order of a year. An estimate of the remineralization time scale associated with the hypothesized eddy injection events can be computed using typical nitracline displacements (90m) and sinking rates of particulate material (1 $\frac{\mathrm{m}}{\mathrm{d}}$). These characteristics imply a restoring time scale of approximately three months, which is considerably shorter than that associated with the pertinent eddy fluctuations. Numerical experiments by McGillicuddy and Robinson (1997) suggest that nutrient transport estimates for eddy-induced upwelling are relatively insensitive to the restoring time scale.

3.3 Advection numerics

The technical details of advection require special attention for biologically reactive tracers, owing to two characteristics which can sometimes set them apart from typical physical tracers. First, biological tracers often vary by orders of magnitude over short spatial scales, making regions of such high gradients prone to significant overshoot/undershoot problems associated with centered-time centered-space algorithms. This issue can become particularly troublesome due to the positive-definite nature of such tracers– even the slightest negative concentrations cause numerical instability in the equations governing biological dynamics.

A variety of different advection schemes have been used in recent intercomparison studies (Hecht *et al.*, 1998; Shchepetkin and McWilliams, 1998; Hasumi and Suginohara, 1999; Griffies *et al.*, 2000). Oschlies and Garcon (1998) compared two positive-definite schemes for tracer advection in their basin-scale biogeochemical model: second order upwind differencing (also used by Sarmiento *et al.*, 1993) and the multidimensional positive definite central differences (MPDCD) of Lafore *et al.* (1998). Results of their biogeochemical model were sensitive to the numerical diffusion implicit in the upwind scheme. Such diffusion is significantly reduced in the MPDCD algorithm. On the basis of the Oschlies and Garcon results, we chose to use MPDCD. Basically, it is a standard centered difference advection scheme with a limit condition placed on the fluxes. The flux limitation ensures that advection cannot remove more scalar than is present at any given time step. This is accomplished by multiplying all fluxes going out of a cell by the factor

$$\min(1.0, \quad VC^{t-\Delta t}/(2\Delta t \Sigma F_i^{out} A_i))$$

where V is volume, C is concentration, t is time, Δt is timestep, F_i^{out} is an outward flux, and A_i is area of a grid cell face. The factor of 2 appears because the leapfrog timestepping then uses the fluxes to compute $C^{t+\Delta t}$. Thus the MPDCD scheme is a simple scaling factor applied to fluxes which is only different from 1.0 if the fluxes would drive the concentration negative. Fortunately, the additional computational cost of this procedure is minor (approximately 10%).

3.4 Results

Mesoscale processes clearly impact new production throughout the basin (Figure 3, right panel; also see `http://science.whoi.edu/users/mcgillic/pop-bgc/pop-bgc.html` for animated presentation of these results). This instantaneous snapshot of the simulated biological uptake term is replete with mesoscale structure in nearly all areas except for the subpolar region where production is still strongly light-limited in mid-June. A zoom view of the solution near the BATS site reveals the detailed relationships between the mesoscale eddy field and nitrate (Figure 4). Although there is some enhancement of nitrate associated with the frontal features in between eddies, the strongest anomalies are in the interiors of the eddy features. This phenomenology is consistent with regional model studies of McGillicuddy and Robinson (1997) and the conceptual model shown in Figure 2.

The final two years of the simulation are sufficient to compute a statistically sound basin-scale map of annual new production (Figure 5). As expected, simulated new production is highest in the northern latitudes and in equatorial upwelling regions. Generally speaking, magnitudes fall within the range of values estimated at several sites around the basin (Table 3). The only exception to this is the BATS site, where the simulated new production

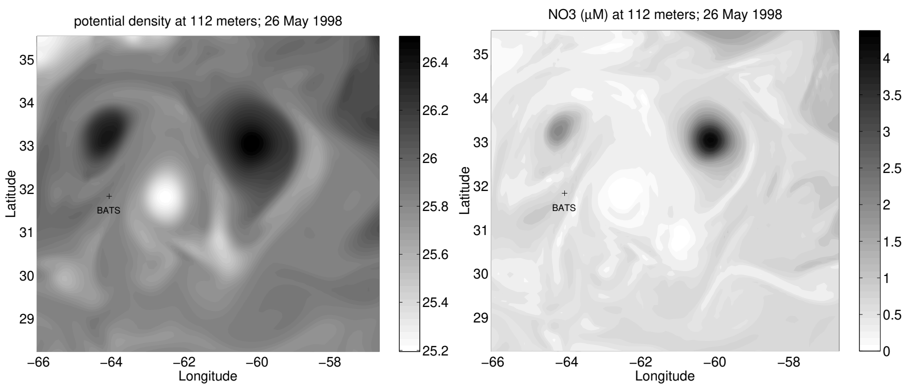


Figure 4: Snapshots of potential density and nitrate in the Sargasso Sea extracted from a 0.1° degree simulation of the North Atlantic.

slightly exceeds the highest estimate for that area. Breakdown of the nutrient budget (Table 4) indicates a disproportionately large share of the annual new production is fueled by wintertime convection. Simulated values of up to 4 mol N m^{-2} yr^{-1} approach the highest values for *total* primary production measured at BATS. This overly large convective input may be a result of excessive mixed layer deepening in the model solution. Time series of the balance of terms (not shown) suggest that vertical advection dominates nutrient supply at all times of year except during winter convection. The total contribution by vertical advection of 0.13 mol N m^{-2} yr^{-1} consists of the eddy-driven nutrient flux in addition to the sink of nutrients caused by the mean Ekman downwelling, which is estimated to be approximately

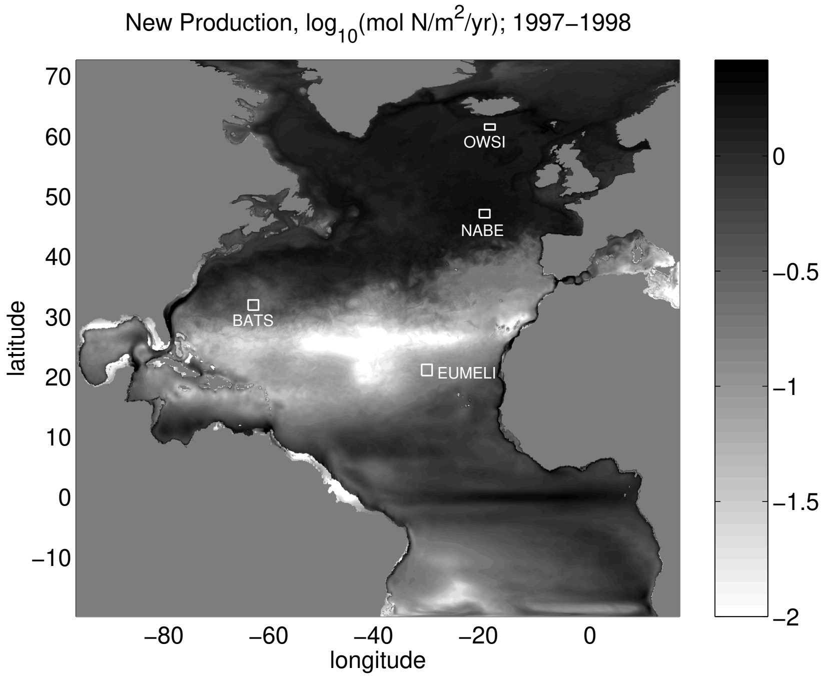


Figure 5: Annual new production ($\log_{10}$ mol N m^{-2} yr^{-1}) averaged over the final two years of a three year simulation.

0.15 mol N m^{-2} yr^{-1} (see above). Thus the simulated eddy-induced nutrient supply is approximately 0.28 mol N m^{-2} yr^{-1}, which is within the range of estimates based on regional approaches (McGillicuddy *et al.*, 1998; Siegel *et al.*, 1999).

	Annual New Production			
Site	Simulated	Observed	Method	Reference
BATS		0.45 ± 0.10	O_2 utilization	Jenkins and Wallace (1995)
(32N,64W)		0.42 ± 0.09		Jenkins and Goldman (1985)
		0.46 ± 0.09	O_2 production	Jenkins and Goldman (1985)
		0.39 ± 0.16		Spitzer and Jenkins (1989)
		0.51 ± 0.14		Spitzer and Jenkins (1989)
		0.56 ± 0.16	He flux gauge	Jenkins (1988)
		0.47 ± 0.15		Jenkins (pers. comm.)
		0.70 ± 0.20		Jenkins (1998)
	0.78	0.39 – 0.70		
NABE		0.90 ± 0.30	PP and O_2 data	Balkanski *et al.* (1999)
(47N,20W)		1.26 ± 0.63	PP and f-ratio	Behrenfeld and Falkowski (1997)
				Buesseler (1998)
				Martin *et al.* (1993)
		0.82 ± 0.44	PP and f-ratio	Antoine *et al.* (1996)
				Buesseler (1998)
				Martin *et al.* (1993)
		2.52 ± 0.63	SeaWiFS and model	Laws *et al.* (2000)
		0.69	seasonal Chl and NO_3	Campbell and Aarup (1992)
		0.43	seasonal Chl and NO_3	Strass and Woods (1991)
	1.40	0.43 – 2.52		
OWS I		0.90 ± 0.30	PP and O_2 data	Balkanski *et al.* (1999)
(59N,19W)		0.80	Apr-Aug NO_3 util.	Sambrotto *et al.* (1993)
		1.92 ± 0.35	PP and f-ratio	Behrenfeld and Falkowski (1997)
				Sambrotto *et al.* (1993)
				Fasham *et al.* (1993)
		0.79 ± 0.16	PP and f-ratio	Antoine *et al.* (1996)
				Sambrotto *et al.* (1993)
				Fasham *et al.* (1993)
		2.52 ± 0.63	SeaWiFS and model	Laws *et al.* (2000)
		0.53	seasonal Chl and NO_3	Campbell and Aarup (1992)
	1.42	0.53 – 2.52		
EUMELI		0.45 ± 0.15	PP and O_2 data	Balkanski *et al.* (1999)
(21N,31W)		0.19 ± 0.16	PP and $\delta^{15}N$ uptake	Morel (1999)
		0.14 ± 0.08	PP and f-ratio	Behrenfeld and Falkowski (1997)
				Morel (1999)
		0.16 ± 0.07	PP and f-ratio	Antoine *et al.* (1996)
				Morel (1999)
		0.10	seasonal Chl and NO_3	Campbell and Aarup (1992)
		0.02	sediment traps	Passow and Peinert (1993)
	0.08	0.02 – 0.15		

Table 3: Annual new production in the North Atlantic (mol N m^{-2} yr^{-1}). Simulated values are compared with the range of observational estimates in the final entry for each site.

	BATS	NABE	OWS I	EUMELI
Horizontal transport	0.07	0.24	-0.57	0.00
advection	0.07	0.23	-0.57	0.00
diffusion	0.00	0.01	0.00	0.00
Vertical mixing	0.58	1.48	1.40	0.04
convection	0.46	1.14	1.09	0.00
diffusion	0.12	0.34	0.31	0.04
Vertical advection	0.13	-0.21	0.50	0.04
Annual New Production	0.78	1.40	1.42	0.08

Table 4: Simulated nitrate budgets and annual new production (mol N m^{-2} yr^{-1}) at four different sites in the North Atlantic.

7. Proposed Research

There has been a great deal of progress in GCM simulations of the North Atlantic circulation since the first coarse resolution runs were conducted in the mid 1980s. The latest generation of simulations contain improvements in a number of aspects, including:

- Time-mean circulation. The spurious upwelling in the western boundary current has been largely overcome. In addition, the problem of the mean position of the Gulf Stream being too far north has also been reduced, resulting in a more realistic pattern of convection in this part of the basin.

- Resolution of eddies. Steadily improving computational capability and numerical modeling methodology have made basin scale eddy resolving simulations a feasible undertaking. Standard 1/3° simulations from the World Ocean Circulation Experiment Community Modeling Effort (*e.g.* Bryan *et al.*, 1995) are probably more appropriately termed "eddy permitting" in the mid-latitudes. However, higher resolution cases have been run at 1/6° (Böning and Budich, 1992; Böning, *et al.*, 1996; Chao, *et al.* 1996), 1/10° (Smith *et al.*, 2000), 1/12° (Paiva *et al.*, 1999) and even 1/64° (Hurlburt and Hogan, 2000). Although increased resolution has clearly improved the realism of such models, intercomparison of model results at 1/10° and higher suggest that aspects of the circulation are sensitive to model architecture and choice of subgridscale parameterization (Chassignet *et al.*, 2000).

- Treatment of the surface boundary layer. Significant interest in fluxes across the air-sea interface has stimulated the development of advanced upper ocean models, such as the "K-profile parameterization" (hereafter KPP) introduced by Large *et al.* (1994). The coupling of surface boundary layer models such as KPP to GCMs has resulted in dramatic improvement in the realism in which upper ocean processes are represented (*e.g.* Large *et al.*, 1997).

All three of these elements potentially impact the fundamental biogeochemical balances in basin scale models. Therefore, the time is right to take the next step in basin-scale biogeochemical modeling, which is *to examine the ramifications of improved simulations of the North Atlantic circulation on our understanding of basin-scale biogeochemistry.* Particular emphasis will be placed on mesoscale processes in light of recent evidence concerning the role of eddies on nutrient supply to the upper ocean. In addition, we plan to investigate the role of *lateral* eddy transports below the euphotic zone. Lee and Williams (submitted) have suggested that such lateral fluxes are necessary to maintain the high nutrient concentrations observed in the deep waters of the main subtropical gyre. This leads us to the following two hypotheses which we wish to test with model simulations:

1. The primary impact of mesoscale eddies on upper ocean ecosystems is the supply of inorganic nutrients through vertical transport processes.

2. Below the well-lit surface layers, the primary influence of mesoscale eddies on biogeochemical cycling is horizontal transport of dissolved materials.

In order to achieve these objectives, the following research plan is proposed.

1. *Sensitivity analysis of the nutrient transport simulations.*

Having established the feasibility and scientific utility of the high-resolution eddy-resolving coupled physical-biogeochemical simulations, we now need to carry out a set of experiments to assess the robustness of the conclusions that can be drawn from them. The primary sensitivities that need to be addressed are associated with the biogeochemical component of the model, including the formulations for biological uptake in surface waters and nutrient remineralization below. However, the physical model is constantly being improved by other investigators, and we hope to incorporate those improvements as they become available. Of particular interest is a more sophisticated treatment of upper ocean boundary layer dynamics to be achieved with the implementation of the KPP mixing scheme into the high-resolution POP model (currently being experimented with at LANL and NCAR).

2. *Incorporation of explicit biogeochemistry: the OCMIP-2 formulation.*

Although the nutrient transport simulations described above have been illuminating, they were designed to examine a specific process: the role of eddies in nutrient supply to the upper ocean. In order to investigate the impacts of mesoscale dynamics on biogeochemical cycling more generally, it will be necessary to incorporate biogeochemical processes into the model explicitly. A wide variety of approaches are possible; we propose to implement the formulation used in the IGBP Ocean Carbon-Cycle Model Intercomparison Project (OCMIP), a research program supported in part by U.S. JGOFS SMP. The first phase of OCMIP focused on simulations of natural and anthropogenic CO_2 and ^{14}C, following standard protocols agreed upon by participants. Models were not only compared among themselves, but also rigorously compared with observations. This strategy has resulted in rapid progress in ocean carbon cycle modeling (Orr, 1999; also see `http://www.ipsl.jussieu.fr/OCMIP/`).

The second phase of OCMIP (OCMIP-2) has broadened to include additional tracers, in addition to a simple five-component biogeochemical model (Najjar and Orr, 1998). The biogeochemical model couples the cycles of phosphorus, oxygen and carbon with state variables for phosphate (PO_4), dissolved organic phosphorus (DOP), oxygen (O_2), dissolved inorganic carbon (DIC) and alkalinity (Alk). One aspect of the model which will need some modification for use in eddy-resolving simulations is the way biological production is handled. In the OCMIP-2 formulation, nutrient uptake by phytoplankton is parameterized via restoring to observed surface nutrient concentrations, as in Najjar *et al.* (1992) and Anderson and Sarmiento (1995). Clearly this will be problematic in a situation where the model contains much smaller scale dynamic phenomena than are present in the nutrient climatology. Therefore we intend to use a more explicit model for biological production, similar to that used in our nutrient transport simulations.

3. *Coupled biogeochemical simulations.*

A hierarchy of experiments are planned using 1.6° and 1/10° simulations. The general experimental design will be to spin-up the coupled model at coarse resolution until statistical equilibrium is achieved as per the OCMIP-2 protocols. Then, the high resolution model will be initialized with that solution and run through some small number (~3) of annual cycles. Although transient behavior associated with disequilibrium in the initial conditions of such biogeochemical models generally dies out within the first year of integration (Sarmiento *et al.* 1993), true statistical steady state cannot be achieved without running the model for thousands of years in order to allow the deep ocean to fully equilibrate. Clearly such lengthy calculations are not feasible at high resolution. Thus, it is necessary to rely on shorter integrations, analyzing the solutions after the initial dynamical adjustment phase has been completed.

Of course, there is a problem intrinsic to such an approach. After spinup of the coupled model at 1.6°, the biogeochemical fields will be in equilibrium with the circulation as represented in the coarse resolution model. When the resolution is increase to 1/10°, not only do eddies emerge, but the mean circulation changes due to eddy-induced transports (Smith *et al.*, 2000). Thus there will be two additional sources of adjustment taking place well beyond the initial period of dynamical adjustment: the biogeochemical solutions will react to both (1) the presence of mesoscale processes, and (2) changes in the mean circulation caused by those very same eddies. It is not immediately clear how to cleanly distinguish between these two contributions– we simply note here that it will pose a challenge to interpretation of the results of the high resolution cases. Nevertheless, this approach will provide a framework in which to assess the impact of mesoscale dynamics on biogeochemical cycling in the North Atlantic.

4. *Parameterization of mesoscale biogeochemical processes.*

Several different lines of evidence, including the high-resolution basin-scale simulations described above, suggest that mesoscale eddies play an important role in nutrient supply to the upper ocean. Thus, it is important to consider methods for parameterizing this process in larger scale (*i.e.* global) models that are necessarily run at coarse resolution. Possible elements of such a parameterization for the process schematized in Figure 2 might include (a) some measure of the root mean square eddy-induced displacement of isopycnals based on the distribution of eddy kinetic energy, and (b) the vertical structure of those displacements in relation to the depths of the nutricline, euphotic zone and mixed layer. As we gain intuition about other impacts of mesoscale dynamics on basin-scale biogeochemistry (such as lateral transports in the deep ocean), we will also consider their parameterization as well. The hierarchy of experiments described in (3) above will provide a useful basis for testing such parameterizations, by including them in the 1.6° case and comparing the results with the higher resolution simulations.

8. Relevance and Significance of the Proposed Work

The research proposed herein touches on all three elements of the U.S. JGOFS SMP research strategy. The numerical experiments described above are directly relevant to the mechanisms which control local, regional and basin-scale carbon balances (JGOFS SMP (elements 1 and 2). Furthermore, the proposed development of parameterizations for mesoscale processes for use in larger scale models will provide a framework for extrapolation of these results in global models (element 3).

9. Collaborative Framework

This interdisciplinary project is a group effort which includes investigators from three institutions: WHOI (D. McGillicuddy, L. Anderson), NCAR (S. Doney) and LANL (M. Maltrud). Supporting letters from Drs. Doney and Maltrud are included in Appendix XX. Collectively, the team's expertise spans all aspects necessary to successfully conduct this research: coupled physical-biogeochemical models, ocean observations, and experience with massively parallel supercomputing.

10. Computational Resources

The simulations proposed herein require substantial amounts of supercomputers time. We were very fortunate to have pilot nutrient transport simulations with the $1/10°$ degree model carried out at LANL by M. Maltrud. In the spring of 2000 we were awarded a large allocation of computer time (16,200 General accounting units, or GAU) from the NCAR Climate Simulation Laboratory (CSL) (see award letter in Appendix XX). Such an allocation is on the order of what will be necessary to carry out the proposed research. In our initial application to NCAR's Scientific Computing Division, we explicitly stated our intention of making this an ongoing activity, in which we would "hope to carry out two high-resolution experiments every twelve months." Should this project be funded, we would apply for annual renewal of our allocation at NCAR's CSL. As we increase the number of biogeochemical constituents included in our model, we will have to expand the request accordingly.

References

[1] L. Anderson and J. Sarmiento, *Global ocean phosphate and oxygen simulations*, Global Biogeochemical Cycles, 9 (1995), pp. 621–636.

[2] D. Antoine, J.-M. Andre, and A. Morel, *Oceanic primary production 2. Estimation at global scale from satellite (Coastal Zone Color Scanner) chlorophyll*, Global Biogeochemical Cycles, 10 (1996), pp. 57–70.

[3] Y. Balkanski, P. Monfray, M. Battle, and M. Heimann, *Ocean primary production derived from satellite data: An evaluation with atmospheric oxygen measurements*, Global Biogeochemical Cycles, 13 (1999), pp. 257–271.

[4] B. Barnier, L. Siefridt, and P. Marchesiello, *Thermal forcing for a global ocean circulation model using a three-year climatology of ECMWF analyses*, Journal of Marine Systems, 6 (1995), pp. 363–380.

[5] M. Behrenfeld and P. Falkowski, *Photosynthetic rates derived from satellite-based chlorophyll concentration*, Limnol. Oceanogr., 42 (1997), pp. 1–20.

[6] C. Boning, F. Bryan, W. Holland, and R. Doscher, *Deep-water formation and meridional overturning in a high-resolution model of the North Atlantic*, Journal of Physical Oceanography, 26 (1996), pp. 1142–1164.

[7] C. Boning and R. Budich, *Eddy dynamics in a primitive equation model: sensitivity to horizontal resolution and friction*, Journal of Physical Oceanography, 22 (1992), pp. 361–381.

[8] C. Boning, W. Holland, F. Bryan, G. Danabasoglu, and J. McWilliams, *An overlooked problem in model simulation of the thermohaline circulation and heat transport in the Atlantic ocean*, Journal of Climate, 8 (1995), pp. 515–523.

[9] F. Bryan, C. Boning, and W. Holland, *On the midlatitude circulation in a high-resolution model of the North Atlantic*, Journal of Physical Oceanography, 25 (1995), pp. 289–305.

[10] K. Buesseler, *The de-coupling of production and particulate export in the surface ocean*, Global Biogeochemical Cycles, 12 (1998), pp. 297–310.

[11] J. Campbell and T. Aarup, *New production in the North Atlantic derived from seasonal patterns of surface chlorophyll*, Deep-Sea Research, 39 (1992), pp. 1669–1694.

[12] Y. Chao, A. Gangopadhyay, F. Bryan, and W. Holland, *Modeling the Gulf Stream system: how far from reality?*, Geophys. Res. Let., 23 (1996), pp. 3155–3158.

[13] E. Chassignet, Z. Garraffo, R. Smith, and H. E. Hurlburt, *High resolution Gulf Stream modeling*, 2000. Submitted to Geophys. Res. Lett.

[14] S. Dutkiewicz, M. Follows, J. Marshall, and W. Gregg, *Interannual variability of phytoplankton abundances in the north atlantic*. In press.

[15] R. Eppley, *Temperature and phytoplankton growth in the sea*, Fishery Bulletin, 17 (1972), pp. 15–24.

[16] P. Falkowski, D. Ziemann, Z. Kolber, and P. Bienfang, *Role of eddy pumping in enhancing primary production in the ocean*, Nature, 352 (1991), pp. 55–58.

[17] M. Fasham, J. Sarmiento, R. Slater, H. Ducklow, and R. Williams, *Ecosystem behavior at Bermuda Station "S" and Ocean Weather Station India: A general circulation model and observational analysis*, Global Biogeochemical Cycles, 7 (1993), pp. 379–415.

[18] S. Griffies, R. Pacanowski, and R. Hallberg, *Spurious diapycnal mixing associated with advection in a z-coordinate ocean model*, Monthly Weather Review, 128 (2000), pp. 538–564.

[19] H. Hasumi and N. Suginohara, *Sensitivity of a global ocean circulation model to tracer advection schemes*, Journal of Physical Oceanography, 29 (1989), pp. 2730–2740.

[20] M. Hecht, F. Bryan, and W. Holland, *A consideration of tracer advection schemes in a primitive equation ocean model*, J. Geophys. Res., 103 (1998), pp. 3301–3321.

[21] S. Hellerman and M. Rosenstein, *Normal monthly wind stress over the world ocean with error estimates*, Journal of Physical Oceanography, 13 (1983), pp. 1093–1104.

[22] H. Hurlburt and P. Hogan, *Impact of 1/8° to 1/64° resolution on Gulf Stream model-data intercomparisons in basin-scale subtropical Atlantic Ocean models*, Dyn. Atmos. Oceans, 32 (2000), pp. 283–329.

[23] G. Hurtt and R. Armstrong, *A pelagic ecosystem model calibrated with BATS data*, Deep-Sea Research, 43 (1996), pp. 653–683.

[24] W. Jenkins, *Oxygen utilization rates in North Atlantic subtropical gyre and primary production in oligotrophic systems*, Nature, 300 (1982), pp. 246–248.

[25] ——, *Nitrate flux into the euphotic zone near Bermuda*, Nature, 331 (1988), pp. 521–523.

[26] ——, *The use of anthropogenic tritium and helium-3 to study subtropical gyre ventilation and circulation*, Phil. Trans. Roy. Soc., 325 (1988), pp. 43–61.

[27] ——, *Studying subtropical thermocline ventilation and circulation using tritium and* ^3He, J. Geophys. Res., 103 (1998), pp. 15,817–15,831.

[28] W. Jenkins and J. Goldman, *Seasonal oxygen cycling and primary production in the Sargasso Sea*, J. Mar. Res., 43 (1985), pp. 465–491.

[29] W. Jenkins and D. Wallace, *Tracer based inferences of new primary production in the sea*, in Primary Productivity and Biogeochemical Cycles in the Sea, P. Falkowski and A. Woodhead, eds., New York, 1992, Plenum Press, pp. 299–316.

[30] B. K., *A numerical method for the study of the circulation of the world ocean*, J. Comp. Phys., (1969), pp. 347–376.

[31] D. Kiefer and B. Mitchell, *A simple, steady-state description of phytoplankton growth based on absorbtion cross-section and quantum efficiency*, Limnol. Oceanogr., 28 (1983), pp. 770–776.

[32] J.-P. Lafore, J. Stein, N. Asencio, P. Bougeault, V. Ducrocq, J. Duron, C. Fischer, P. Hereil, P. Mascart, V. Masson, J. Pinty, J. Redelsperger, E. Richard, and J. V.-G. de Arellano, *The meso-nh atmospheric simulation system, I, Adiabatic formulation and control simulations*, Annales Geophysicae, 16 (1998), pp. 90–109.

[33] W. Large, G. Danabasoglu, S. Doney, and J. McWilliams, *Sensitivity to surface forcing and boundary layer mixing in a global ocean model: annual-mean climatology*, 1997. in press.

[34] W. Large, J. McWilliams, and S. Doney, *An oceanic vertical mixing scheme with a k-profile boundary layer parameterization*, Rev. Geophys., 32 (1994), pp. 363–403.

[35] E. Laws, P. Falkowski, W. Smith, H. Ducklow, and J. McCarthy, *Temperature effects on export production in the open ocean*, Global Biogeochemical Cycles, (2000). Global Biogeochem. Cycles, in press.

[36] J. Ledwell, A. Watson, and C. Law, *Evidence for slow mixing across the pycnocline from an open-ocean tracer-release experiment*, Nature, 364 (1993), pp. 701–703.

[37] ——, *Mixing of a tracer released in the pycnocline of a subtropical gyre*, 1997. Submitted, *Journal of Geophysical Research*.

[38] M. Lee and R. Williams, *Examining how eddies affect biological production through lateral transport and diffusion of nutrients*, 2000. Submitted, *J. Mar. Res.*

[39] S. Levitus, *Climatological atlas of the world ocean*, in NOAA Prof. Paper No. 13, U.S. Govt. Printing Office, Washington DC, 1982, p. 173pp.

[40] M. Lewis, W. Harrison, N. Oakley, D. Hebert, and T. Platt, *Vertical nitrate fluxes in the oligotrophic ocean*, Science, 234 (1986), pp. 870–873.

[41] J. Liebig, *On chemical processes in the nutrition of vegetables*, in Chemistry and its applications to agriculture and physiology, L. Playfair, Peterson, PA, 1845.

[42] J. Martin, S. Fitzwater, R. Gordon, C. Hunter, and S. Tanner, *Iron, primary production and carbon-nitrogen flux studies during the JGOFS North Atlantic Bloom Experiment*, Deep-Sea Research, 40 (1993), pp. 115–134.

[43] D. McGillicuddy, V. Kosnyrev, J. Ryan, and J. Yoder, *Covariation of mesoscale ocean color and sea surface temperature patterns in the Sargasso Sea.* Accepted, *Deep-Sea Research.*

[44] D. McGillicuddy and A. Robinson, *Eddy induced nutrient supply and new production in the Sargasso Sea*, Deep-Sea Research, 44 (1997), pp. 1427–1449.

[45] D. McGillicuddy, A. Robinson, D. Siegel, H. Jannasch, R. Johnson, T. Dickey, J. McNeil, A. Michaels, and A. Knap, *Influence of mesoscale eddies on new production in the Sargasso Sea*, Nature, 394 (1998), pp. 263–265.

[46] J. McNeil, H. Jannasch, T. Dickey, D. McGillicuddy, M. Brzezinski, and C. Sakamoto, *New chemical, bio-optical and physical observations of upper ocean response to the passage of a mesoscale eddy off Bermuda*, J. Geophys. Res., 104 (1999), pp. 15,537–15,548.

[47] A. Michaels, A. Knap, R. Dow, K. Gundersen, R. Johnson, J. Sorenson, A. Close, G. Knauer, S. Lohrenz, V. Asper, M. Tuel, and R. Bidigare, *Seasonal patterns of ocean biogeochemistry at the U.S. JGOFS Bermuda Atlantic Time-series Study site*, Deep-Sea Research, 41 (1994), pp. 1013–1038.

[48] F. Morel, *Process studies in eutrophic, mesotrophic and oligotrophic regimes within the tropical northeast Atlantic*, in The changing carbon cycle, IGBP Book Ser., R. Hanson, H. Ducklow, and J. Field, eds., Cambridge University Press, New York, 1999, pp. 338–374.

[49] R. Najjar and J. Orr, *Design of OCMIP-2 simulations of chlorofluorocarbons, the solubility pump and common biogeochemistry*, 1998. See "Design Protocols" at `http://www.ipsl.jussieu.fr/OCMIP/phase2/#simulations`.

[50] R. Najjar, J. Sarmiento, and J. Toggweiler, *Downward transport and fate of organic matter in the ocean: simulations with a general circulation model*, Global Biogeochemical Cycles, 6 (1992), pp. 45–76.

[51] J. Orr, *Ocean Carbon-Cycle Model Intercomparison Project (OCMIP): Phase 1 (1995-1997)*, Tech. Rep. GAIM Report 7, IGBP/GAIM Office, EOS, Univ. New Hampshire, Durham, NH, USA, 1999.

[52] A. Oschlies and V. Garcon, *An eddy-permitting coupled physical-biological model of the North Atlantic 1. Sensitivity to advection numerics and mixed layer physics*, Global Biogeochemical Cycles, 13 (1999), pp. 135–160.

[53] A. Oschlies, W. Koeve, and V. Garcon, *An eddy-permitting coupled physical-biological model of the North Atlantic 2. Ecosystem dynamics and comparison with satellite and JGOFS local studies data*, Global Biogeochemical Cycles, 14 (2000), pp. 499–523.

[54] R. Pacanowski and S. Philander, *Parameterization of vertical mixing in numerical models of tropical oceans*, Journal of Physical Oceanography, 11 (1981), pp. 1443–1451.

[55] A. Paiva, J. Hargrove, E. Chassignet, and R. Bleck, *Turbulent behavior of a fine mesh (1/12°) numerical simulation of the North Atlantic*, Journal of Marine Systems, 21 (1999), pp. 307–320.

[56] U. Passow and R. Peinert, *The role of plankton in particle flux: two case studies from the northeast Atlantic*, Deep-Sea Research II, 40 (1993), pp. 573–585.

[57] T. Platt, C. Gallegos, and W. Harrison, *Photoinhibition of photosynthesis in natural assemblages of marine phytoplankton*, J. Mar. Res., 38 (1980), pp. 687–701.

[58] P. Richardson, *A census of eddies observed in north atlantic SOFAR float data*, Progress in Oceanography, 31 (1993), pp. 1–50.

[59] R. Sambrotto, J. Martin, W. Broenkow, C. Carlson, and S. Fitzwater, *Nitrate utilization in surface waters of the Iceland Basin during spring and summer of 1989*, Deep-Sea Research II, 40 (1993), pp. 441–457.

[60] J. Sarmiento, G. Thiele, R. Key, and W. Moore, *Oxygen and nitrate new production and remineralization in the North Atlantic subtropical gyre*, J. Geophys. Res., 95 (1993), pp. 18303–18315.

[61] E. Schulenberger and J. Reid, *The Pacific shallow oxygen maximum, deep chlorophyll maximum, and primary productivity, reconsidered*, Deep-Sea Research, 28A (1981), pp. 901–919.

[62] A. Shchepetkin and J. McWilliams, *Quasi-monotone advection schemes based on explicit locally adaptive dissipation*, Monthly Weather Review, 126 (1998), pp. 1541–1580.

[63] D. Siegel, D. McGillicuddy, and E. Fields, *Mesoscale eddies, satellite altimetry and new production in the Sargasso Sea*, J. Geophys. Res., 104 (1999), pp. 13,359–13,379.

[64] R. Smith, J. Dukowicz, and R. Malone, *Parallel ocean circulation modeling*, Physica D, 60 (1992), pp. 38–61.

[65] R. Smith, M. Maltrud, F. Bryan, and M. Hecht, *Numerical simulation of the North Atlantic Ocean at 1/10°*, Journal of Physical Oceanography, 30 (2000), pp. 1532–1561.

[66] W. Spitzer and W. Jenkins, *Rates of vertical mixing, gas exchange and new production: estimates from seasonal gas cycles in the upper ocean near Bermuda*, J. Mar. Res., 47 (1989), pp. 169–196.

[67] V. Strass and J. Woods, *New produciton in the summer revealed by the meridional slope of the deep chlorophyll maximum*, Deep-Sea Research, 38 (1991), pp. 35–56.

[68] R. Williams and M. Follows, *The Ekman transfer of nutrients and maintenance of new production over the North Atlantic*, Deep-Sea Research, 45 (1997), pp. 461–489.

[69] J. Woods, *Mesoscale upwelling and primary production*, in Toward a Theory on Biological-Physical Interactions in the World Ocean, B. Rothschild, ed., Dordrecht, 1988, D. Reidel.