

## Project Summary

This is a request to the National Science Foundation to support an interdisciplinary research team from Rutgers University, the University of Maine, and the University of Massachusetts to participate in the Pan-Regional Synthesis and Modeling phase of the U.S. GLOBEC Program.

This proposal addresses several mechanisms by which freshwater influx might impact the primary production of *Calanus finmarchicus* in the northern North Atlantic Ocean. Variability in the winter North Atlantic Oscillation index is related to changes in various physical and biological parameters across the entire North Atlantic, but the mechanisms underlying those relationships are not well known. Understanding basin-to-regional connections is important for interpreting patterns of variability observed on both sides of the Atlantic during the core GLOBEC study period (1993-1999) and from earlier observations, and inferring process, whether local or remote, from those observed patterns. The proposed research is focused on: (1) comparing and contrasting the impact of freshwater influx to the eastern and western sides of the North Atlantic, (2) understanding the development and maintenance of a possible three-gyre configuration of *Calanus finmarchicus* distribution in the North Atlantic, and (3) predicting the projected trends and variations in the North Atlantic Ocean based on IPCC projections for upcoming decades.

### Intellectual merit

This proposal seeks a synthetic understanding of how basin- and global-scales changes in climate force physical processes that in turn determine local- and regional-scale biological communities, with a particular focus on freshwater forcing of circulation, mixing, and marine ecosystems within the North Atlantic Ocean. It is pan-regional in scope, building upon the successes of the U.S. GLOBEC program in the Western North Atlantic (and its other regions) to address climate variability issues spanning the entire northern North Atlantic Ocean. Its research approaches include: synthesis of datasets across the North Atlantic, multi-scale coupled physical/biological modeling, and comparative regional studies. In all these respects it responds directly to the U.S. GLOBEC Pan-Regional Synthesis Announcement of Opportunity.

### Broader impacts

Two graduate students will participate in this project. Results will be disseminated by peer-reviewed scientific publications, presentations at national conferences, and to other Pan-Regional GLOBEC investigators (*e.g.*, Greene and colleagues). We will make the model output available via the Rutgers OPeNDAP server. We will give public lectures in Schools of Massachusetts, Maine and New Jersey on the importance of NAO and its impact on the regional ecosystem as part of our ongoing K-12 outreach program. The forecast scenarios for the next two decades will increase awareness of Climate Change. Note that Dr. Fei Chai is a New Investigator to the GLOBEC program and will bring considerable expertise from his associations in the Pacific and in the Climate Change communities. Finally, this project sets the stage for post-GLOBEC end-to-end studies in the North Atlantic (*e.g.*, the BASIN program).

## PROJECT DESCRIPTION

### RESULTS OF PRIOR NSF SUPPORT

**Avijit Gangopadhyay:** Award No. **ANI-0124945** (Internet2 Connection for the University of Massachusetts Dartmouth's School for Marine Science and Technology, (Co-investigator; W. Brown, Principal Investigator), NSF, **6/1/2002-9/30/2003, \$150,000**. provided expertise to help set up Internet2 technology at SMAST for large datasets and model output transfer between modeling groups at SMAST, Harvard, JPL/NASA and JHU/APL. (AG-2): Award No. **OCE0535379** (GLOBEC/NWA: (*Impacts of Climate and Basin-Scale Variability on Seeding and Production of Calanus Finmarchicus in the Gulf of Maine/Georges Bank region*) (PI), **1/1/06-12/31/2008, \$213,119**. The primary objective of the research is to probe the connections between *Calanus finmarchicus* distributions and the physical oceanographic properties, climate variability, and basin-scale circulation changes that are likely to affect the copepod's transport onto Georges Bank. We are doing this using a combination of numerical model simulations and observational data. We have set up a 1/6 degree ROMS over North Atlantic and successfully run basin-scale simulations during low- and high-NAO periods and for the 1980-1999 period. Results are being written up now for four publications. Two graduate student and two postdocs have worked on different components of this project. Many aspects of these results are described in this proposal in Section 2.2.

**James J. Bisagni: Collaborative Research: GLOBEC-01: Patterns of energy flow and utilization on Georges Bank,** (Co-investigator; D. Gifford, Principal Investigator), NSF, 2002-2006, \$127,593. (NSF Award OCE-0217122) This project synthesized key aspects of production and energy flow, based on US-GLOBEC studies in the Northwest Atlantic, and augmented the US-GLOBEC data with information from other sources on production processes at the lower and upper levels of the food web. Different decadal-scale time periods that reflected differing environmental (principally temperature) and fish community regimes were considered (Steele *et al.*, 2007). Work performed by Dr. Bisagni included assembling a climatology of nitrate + nitrite (NO<sub>3</sub>+NO<sub>2</sub>) data to calculate a proxy for new primary production, termed "potential new production" (PNP) as the difference between an integrated or "storage" nitrate + nitrite term (integrated to the depth of the euphotic zone) and a vertical nitrate + nitrite -flux term (Bisagni, 2003) for three hydrographic provinces in and around Georges Bank.

**GLOBEC-01: The physical oceanography of Georges Bank and its impact on biology,** (Co-investigator; R. Beardsley, Principal Investigator), NSF, 2002-2006, \$104,863. (NSF Award OCE-0227679) Comprehensive analysis of sixteen-years (1985-2000) of satellite-derived SST data from eastern GB and western Scotian Shelf revealed strong interannual variability (IAV) for the presence of cold temperature anomalies (colder than -1 °C), defined herein to signify SSWCs (Brunner *et al.*, in revision; Brunner, 2007). A simple Ekman coastal plume model reproduces the general seasonal cycle of the SSF along with the east-west phase shift, except in easternmost regions where SSF positional variability is maximal. Interannual variability (IAV) of the annual mean SSF position between Cape Hatteras and the Tail of the Grand Banks from longitude-time plots reveals alternating bands of offshore (late-1970s, late-1980s, late-1990s) and onshore (early-1980s, early-1990s, early-2000s) annual mean SSF anomaly values, exhibiting a period of approximately 10 years (Bisagni *et al.*, in press).

**Dale Haidvogel and Enrique Curchitser:** Nested Interdisciplinary Models for the Gulf of Alaska (**OCE-0113461, 03/15/01-02/28/07, \$571,564**) and Effects of Seasonal and Interannual Variability of Zooplankton Populations in the California Current System using Coupled Biophysical Models (**OCE-0002893; 07/01/00-06/30/05, \$759,000**): We have developed a suite of coupled physical/ecosystem models to explore the mechanisms by which interannual/interdecadal variability of physical fields affect the production of GLOBEC target zooplankton species and the feeding of juvenile salmon in the Coastal Gulf of Alaska (CGOA) and the California Current System (CCS). A key element in this plan has been our implementation of a suite of basin-, regional-, and local-scale circulation models, linked via one-way coupling. These nested domains include: a basin-scale model encompassing the North Pacific Basin at 20-40 km resolution (NPac), a regional model at ~10 km resolution spanning the Northeast Pacific (NEP), and finally local models at ~3 km resolution in regions of specific interest to U.S. GLOBEC [CCS and CGOA]. Publications resulting thus far include Hermann *et al.* (2002a, b), Curchitser *et al.* (2005),

Powell *et al.* (2006), and Weingartner *et al.* (2002). Data from these simulations has been provided for use in many other regional modeling studies (*e.g.*, Gan *et al.*, 2006). Over 70 presentations, some including immersive visualization of model output, have been given by the PIs at conferences, workshops and schools on various aspects of this work. Output is viewable through a Live Access Server: <http://ferret.pmel.noaa.gov/FOCI/servlets/dataset>.

**Fei Chai:** has had a number of NSF proposals during the past ten years. The most recent two NSF supported projects are: OCE-0137272, Collaborative Research: Biogeochemical Modeling of Carbon Partitioning in the Pacific: the Role of Si and Fe in Regulating Production by Siliceous and Calcifying Phytoplankton, \$246,418, 4/1/2002-3/31/2006 and OCE-0322074, and Collaborative Research: Plankton dynamics and carbon cycling in the equatorial Pacific Ocean: Control by Fe, Si and grazing, \$168,175, 12/1/2003-11/30/2007. These two projects incorporated the silicate pump hypothesis and Fe limitation into an ecosystem model, Carbon, Silicate, and Nitrogen Ecosystem (CoSINE), to simulate air-sea CO<sub>2</sub> fluxes in the Pacific Ocean (Chai *et al.*, 2002; Dugdale *et al.*, 2002). Both 1-D and 3-D CoSINE models were used to test ideas about silicate and iron regulation on phytoplankton productivity for various regions in the Pacific Ocean, as well as the ecosystem response to interannual and decadal climate variability in the Pacific (Chai *et al.*, 2003; Jiang and Chai, 2006). Detailed nutrients (nitrate and silicate) transports by various physical processes in the equatorial Pacific were calculated, and uptake of nutrients in the euphotic zone and remineralization at the depth were evaluated with the measured rates and nutrient profiles (Jiang *et al.*, 2003; Jiang and Chai, 2005). Role of iron in regulating phytoplankton growth was investigated with iron addition experiments in the model, and the modeled results were compared with IronEx II field observations (Chai *et al.*, 2007). Also, a third phytoplankton functional group, coccolithophorids, was incorporated into the latest CoSINE model, which allows us to investigate particulate inorganic carbon (PIC) production and export (Fujii and Chai, 2007). These two projects provided partial salary support and/or research opportunities for 3 graduate students, 3 post-docs and several undergraduates. To date, 14 publications have been supported by these two NSF grants, which are listed in Chai's CV or in the reference section with “\*”.

## 1. Introduction, Motivation and Background

“The importance of comparative analysis in U.S. GLOBEC for pan-regional synthesis has been recognized from the inception of the program. Comparison of the dynamics of closely related taxa selected as target species in relation to specific physical processes (including stratification, mechanisms of retention and loss, upwelling and downwelling, and cross-front exchange) will be an integral component of the overall synthesis and integration effort in U.S. GLOBEC.” (U.S. GLOBEC Synthesis Implementation Plan, 2007).

This proposal addresses several mechanisms by which freshwater influx (or the lack thereof) might impact the population dynamics and production of *Calanus finmarchicus* in the North Atlantic. Variability in the winter North Atlantic Oscillation (NAO) index is related to changes in various physical and biological parameters across the entire North Atlantic, but the mechanisms underlying those relationships are not well known. Understanding basin-to-regional connections is important for interpreting patterns of variability observed on both sides of the Atlantic during the core GLOBEC study period (1993-1999) and from earlier observations (*e.g.*, MARMAP, CPR), and inferring process, whether local or remote, from those observed patterns. The proposed research is focused on: (1) comparing and contrasting the impact of freshwater influx to the eastern and western sides of the North Atlantic, (2) understanding the development and maintenance of a possible three-gyre configuration of *Calanus finmarchicus* distribution in the North Atlantic, and (3) predicting the projected trends and variations in the North Atlantic Ocean based on IPCC projections for upcoming decades.

In order to address these objectives, we will:

- (i) simulate basin-scale circulation fields for the GLOBEC decade of 1990-1999 using an eddy-resolving, validated model extended to include sea ice and riverine inputs of fresh water,
- (ii) utilize a 10-component (lower trophic level) biogeochemical model to understand the biophysical pathways connecting the three *Calanus* gyres during 1990-1999, and
- (iii) forecast the next 20 years of the state of the North Atlantic Ocean using idealized forcing fields (wind curl, heat flux, E-P) representing IPCC scenarios of climate change.

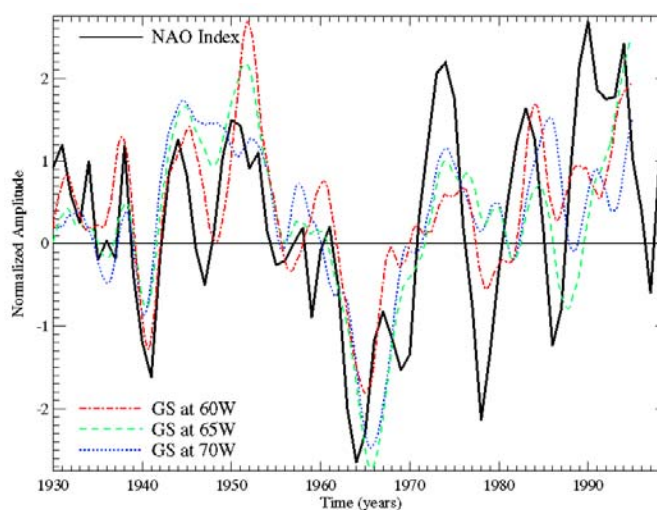
Finally, we will

- (iv) compile and use datasets on salinity, ice cover, IPCC scenarios, river discharge, hydrography, and *Calanus* abundances from the eastern and western North Atlantic to examine potential climate-related mechanisms influencing the Gulf Stream system, North Atlantic Current, and *Calanus* productivity and population dynamics in the North Atlantic Basin.

### 1.1 NAO-Related Oceanic Variability in the Gulf Stream System

The NAO is defined as an alternation of atmospheric mass between the sub-polar low centered over Iceland and the sub-tropical high centered over the Azores. It is the largest single factor affecting atmospheric circulation variability over the North Atlantic Ocean, containing over one-third of the large-scale atmospheric pressure variance during winter (Hurrell *et al.*, 2003). The NAO signal is discernible throughout the year, but is strongest in winter (Hurrell *et al.*, 2003) when it becomes the dominant mode of atmospheric variability influencing temperature and precipitation in the North Atlantic Ocean (Marshall *et al.*, 2001). The NAO wintertime index (NAOWI), based upon the normalized sea level pressure difference between Lisbon, Portugal, and Reykjavik, Iceland, from December-March, has been shown to capture much of the variability in atmospheric perturbations over the North Atlantic Ocean over a wide range of time scales, over past decades, from multi-decadal to interannual (Hurrell *et al.*, 2003). Some patterns are evident/striking: the 1960's show a mostly negative NAOWI, while the 1970's to early 1990's show a largely positive NAOWI. One major exception is that the 1996 NAOWI (computed for the December 1995-March 1996 time period and assigned to 1996) shows the largest single 1-year decrease ever recorded (Greene and Pershing, 2007), to a strongly negative value of  $-3.78$  for 1996 from  $+3.96$  for 1995.

Recent studies suggest that the NAO has a great impact on the surface circulation of the North Atlantic (Hoerling *et al.*, 2001; Visbeck *et al.*, 2003). One of its major manifestations takes the form of north-south oscillations of the Gulf Stream. Using data from 1966 to 1996, Taylor and Stephens (1998) show that over the 30-year period, the position of the Gulf Stream north wall (GSNW) could be reliably determined on the basis of the NAOWI, but with a lag of about 2 years. Gangopadhyay *et al.* (1992) attribute this lag to propagating Rossby waves. Their observations reveal that the delayed-response predictability for the 1977 to 1988 period was a regular feature of the Gulf Stream system for the last 30 years. **Figure 1** shows time series of the Gulf Stream position as defined by the position of the  $15^{\circ}\text{C}$  isotherm



**Figure 1.** Multi-decadal normalized amplitude time series of Gulf Stream ( $15^{\circ}\text{C}$  isotherm position) at  $60^{\circ}\text{W}$ ,  $65^{\circ}\text{W}$ , and  $70^{\circ}\text{W}$  longitude and winter NAO index.

(Parker *et al.*, 1995) overlaid with the NAOWI (K. Drinkwater, pers. comm.). A dominant signal in both Gulf Stream position and NAOWI is the upward trend from 1970 to present (Conversi *et al.*, 2001; Taylor and Gangopadhyay, 2001), and an apparent downward trend from 1950 to 1970. While the Gulf Stream attained its southernmost position during the 1960s, it attained its northernmost positions during the 1950s and 1980s, in congruence with fluctuations in the NAOWI. Over shorter time scales, the Gulf Stream also exhibits interannual fluctuations with a mode of 3 to 5 years.

It has been hypothesized that interannual variability in the position of the GSNW is linked to the “spilling” of cooler, lower-salinity shelf water into the Slope Water Sea south of Nova Scotia (Rossby, 1999). This hypothesis implies that the Gulf Stream’s trajectory and interactions with the Slope Water Sea and shelf may be responding to remote climate forcing mediated by the buoyancy-driven Labrador Current System and not simply to climate-associated variations in the wind-stress curl driving the subtropical gyre (Gangopadhyay and Chao, 2000).

## 1.2 NAO-Related Freshwater/Salinity Variability in the Western North Atlantic (WNA)

The phase changes of the NAO have been correlated with significant regional responses of physical properties and marine ecosystems in the western North Atlantic including Georges Bank (GB; MERCINA, 2004), the Gulf of Maine (GoM; MERCINA, 2001; 2003; 2004), and the Scotian Shelf (SS; Sameoto, 2001; 2004). Temperature and salinity variability in the GoM/GB region during the 90s has been well documented. Mountain (2004) analyzed the temperature and salinity in NAFO subareas 5 and 6 during the 1990s and discovered that the surface waters in the GoM/GB region underwent a gradual freshening (Figure 2) when compared to an earlier period (1978-87) due to an increased inflow of Scotian Shelf Water. Drinkwater (2004) investigated atmospheric and sea-ice conditions in the northwest Atlantic during 1991-2000 and related them to low and high-NAO conditions. The atmospheric low-pressure system over the northwest Atlantic shifted eastward during the latter half of the decade, causing weaker northwesterly winds, warmer temperatures in the Labrador Sea to the Gulf of Maine and a reduction of sea ice.

Fratantoni and Pickart (2006) analyzed twelve years (1990-2001) of hydrographic data to examine alongstream evolution of the shelfbreak front in the western North Atlantic from the west coast of Greenland to the Mid-Atlantic Bight. They found that the shelfbreak front in the Labrador Sea is composed of two fronts: one inshore with fresher Labrador Sea water, and the other offshore with Irminger Sea water. The latter front completely disappears near the Grand Banks. They also found that during the 1990s there was an alongstream freshening of the shelfbreak flow right after the tail of the Grand Banks, even before the front is joined by the freshwater plume outflow from the Gulf of St. Lawrence. They suggest that the outer “salty” portion of the front turns offshore at the tail of the Grand Banks and the fresher surface layer follows the shelfbreak towards the GoM/GB region.

Greene and Pershing (2007) were the first to suggest that the major salinity anomalies observed on Georges Bank, which peaked in 1991 and 1996, were the downstream manifestation of major climatic changes occurring in the Arctic. Relative to the 1980s, the decade of the 1990s was characterized by an increase in the amount of low-salinity water exiting the Arctic Ocean and entering the North Atlantic through the Canadian Archipelago and

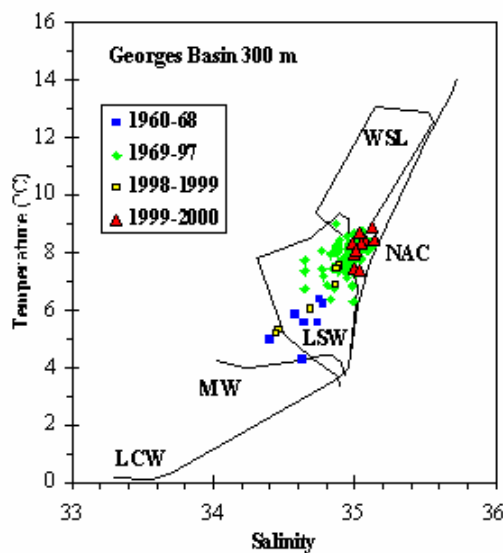


Figure 2. Historical monthly-mean temperature and salinity distribution from 300 (+/- 25m) depth within the Georges Basin subarea as defined by Petrie and Drinkwater. (1993).

Fram Strait (Proshutinsky *et al.*, 2002; Steele *et al.*, 2004). These low-salinity pulses freshened shelf waters from the Labrador Sea to the Middle Atlantic Bight (Loder *et al.*, 2001; Smith *et al.*, 2001; Häkkinen, 2002; Mountain, 2002; 2003; Frank, 2003; Belkin, 2004). The freshening altered stratification and circulation patterns and was hypothetically linked to a regime shift in the shelf ecosystems of the NW Atlantic (Greene and Pershing, 2007).

### 1.3 NAO-Related Freshwater/Salinity Variability in the Eastern North Atlantic (ENA)

In contrast to the western North Atlantic, the salt content in the eastern North Atlantic has gone up during the 1990s (Bethke *et al.*, 2006). Positive salinity trends have been observed in the tropics (Curry *et al.*, 2003; Boyer *et al.*, 2005) and freshening trends in the subpolar Atlantic (Dickson *et al.*, 2002, Curry *et al.*, 2003; Curry and Mauritzen, 2005). The phase changes of the NAO have been correlated with significant regional responses of marine ecosystems in the eastern North Atlantic, including the Baltic Sea (Hanninen *et al.*, 2000; Alheit *et al.*, 2005); Barents Sea (Ottersen and Stenseth, 2001); Bay of Biscay, Celtic Sea and English Channel (Beaugrand *et al.*, 2002); Mediterranean Sea (Moliner *et al.*, 2005); and North Sea (Reid *et al.*, 2001; Lynam *et al.*, 2004).

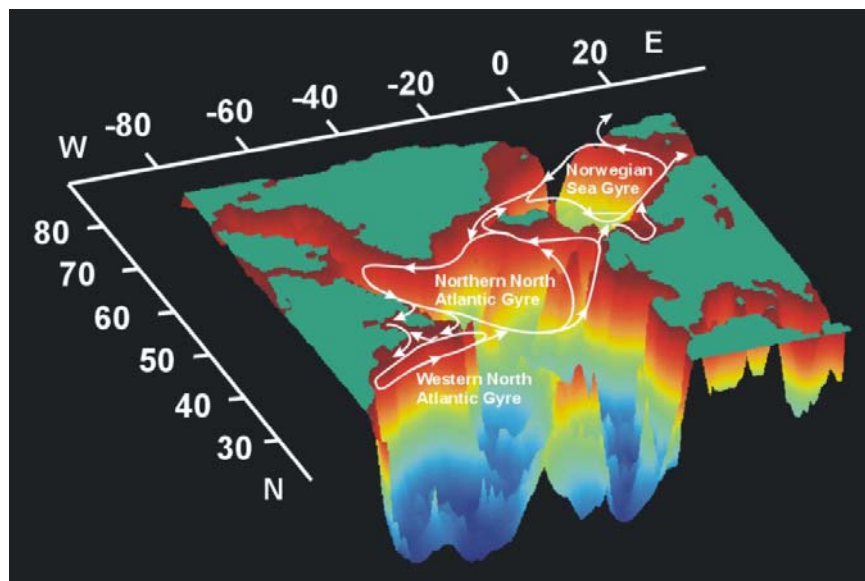
The responses of shelf ecosystems to NAO forcing have been investigated extensively in the NE Atlantic (see reviews by Ottersen *et al.*, 2001; Drinkwater *et al.*, 2003; Stenseth *et al.*, 2005). Much of the success in these investigations can be attributed to the long time series of environmental data available from the shelf ecosystems of the British Isles and Europe, especially those of the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) Continuous Plankton Recorder (CPR) Survey (Reid *et al.*, 1998). Interpretations of the processes associated with NAO forcing initially focused on wind-driven mixing and its influence on stratification and planktonic production (Dickson *et al.*, 2003). Subsequently, the relative roles of local environmental warming, advection, and biotic interactions were examined in the context of the replacement of *Calanus finmarchicus* by *Calanus helgolandicus* as the biomass-dominant zooplankton species in the North Sea (Fromentin and Planque, 1996; Reid *et al.*, 2003; Bonnet *et al.*, 2005; Helaouet and Beaugrand, 2007). As appreciation for the complexity of climate impacts on NE Atlantic ecosystems has grown within the scientific community, efforts to distinguish among the effects of the NAO, other modes of natural climate variability (*e.g.*, the Great Salinity Anomaly (GSA)), and anthropogenic climate change has become a major research imperative (Edwards *et al.*, 2002; Beaugrand *et al.*, 2002).

### 1.4 The Three-Gyre Plankton Distribution in the North Atlantic Basin

The copepod *Calanus finmarchicus* is a unique target species in that it is the most abundant copepod in the North Atlantic and is distributed across the entire ocean basin around three population centers: the Norwegian Sea, the Labrador Sea, and the NW Atlantic Slope Sea. Each center is associated with a semi-enclosed circulation system (Heath *et al.* 2001). The circulation appears to allow each basin to support self-sustaining populations of *Calanus finmarchicus*, but the lack of strong genetic differentiation among the three populations suggests significant exchange and interaction between the regions (Bucklin *et al.*, 2000). Understanding this apparent three-gyre *Calanus finmarchicus* distribution is one of the grand challenges for North Atlantic GLOBEC programs. See **Figure 3** for their geographical coverage and possible linkages.

The proportion of *Calanus* in the total omnivorous zooplankton biomass in the North Sea has declined from a high level of around 40% in the 1960's to less than 5% in the late 1990's. Although the relationship between *Calanus* abundance and cod recruitment is by no means simple (Drinkwater and Frank, 2001), the consequences of such a decline in a major prey species have to be taken into account when looking at the causes of long-term decline in cod populations. The abundance and recruitment of commercially important fish stocks and protected cetacean populations in these ecosystems also have been linked to

phase changes in the NAO (Attrill and Power, 2002; Beaugrand *et al.*, 2002; Drinkwater *et al.*, 2000; Greene *et al.*, 2003; Greene and Pershing, 2007; Brodziak and O'Brien, 2005; Perry *et al.*, 2005).



**Figure 3.** The three-gyre plankton distribution in the North Atlantic.

## 2. Methodologies and Synthesis Results from Prior Research

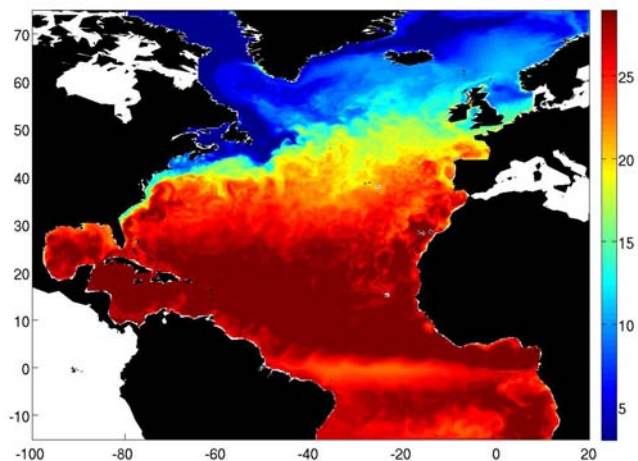
We propose below a pan-regional study of circulation and population dynamics in the sub-polar North Atlantic Ocean. The proposed pan-regional synthesis relies upon successful approaches and results obtained in prior GLOBEC, and non-GLOBEC, research efforts. We briefly review the following.

### 2.1 The Regional Ocean Circulation Modeling System (ROMS)

The circulation model we will use is the Regional Ocean Modeling System (ROMS) <http://marine.rutgers.edu/po/index.php?model=roms>, which has been developed and is supported by a consortium of institutions including Rutgers University, UCLA and NASA/JPL. Haidvogel *et al.* (2007) describe in detail the algorithms that comprise the ROMS computational kernel. This kernel utilizes consistent temporal averaging of the barotropic mode to guarantee both exact conservation and constancy preservation properties for tracers and therefore more accurately resolves barotropic processes, while preventing aliasing of unresolved barotropic signals into the slow baroclinic motions. Accuracy of the mode-splitting is further enhanced due to redefined barotropic pressure-gradient terms to account for the local variations in the density field (*i.e.*, the pressure-gradient truncation error is greatly reduced). Vertical interpolation is based on conservative parabolic splines. Of importance for this proposal, ROMS includes provision for sea ice dynamics (following Budgell, 2005) and multiple levels of one-way nesting. It has been successfully coupled to a variety of Eulerian biogeochemical and Lagrangian individual-based sub-models (*e.g.*, Fennel *et al.*, 2006), and has been successfully applied and validated in all four of the U.S. GLOBEC study regions (Hermann *et al.*, 2002a,b; Curchitser *et al.*, 2005; Powell *et al.*, 2006; Chaudhuri *et al.*, 2007; Chaudhuri *et al.* in prep; Dinniman *et al.*, 2003; Dinniman and Klinck, 2004; Dinniman *et al.*, 2007).

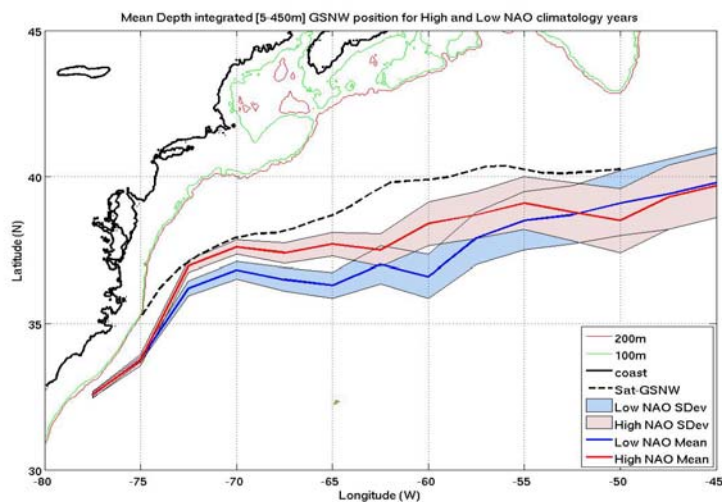
## 2.2 Ongoing Basin-scale Modeling for Simulating Responses to High and Low NAO Events

Our ongoing work under GLOBEC Phase IVB involves the physical modeling of the North Atlantic basin for the GLOBEC study period. The North Atlantic region is simulated at  $1/6^\circ$  horizontal resolution and 50 vertical levels. The initial fields for the model including temperature and salinity are configured for the North Atlantic grid using Levitus climatology. The domain is shown in **Figure 4**.



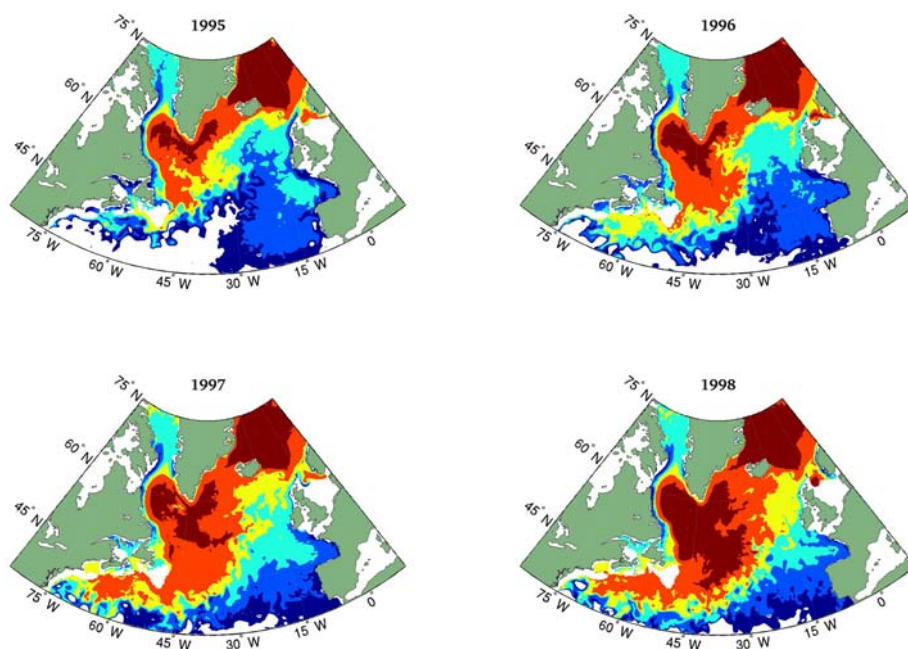
**Figure 4:** Snapshot of ROMS model simulation of the North Atlantic. The model domain ranges from  $-100^\circ\text{W}$  to  $20^\circ\text{E}$  and  $15^\circ\text{S}$  to  $75^\circ\text{N}$ . The snapshot is taken from the high NAO simulation on Jul 30<sup>th</sup>.

During the first year of this project, a number of sensitivity analyses with heat flux and wind forcing were carried out, and the NCEP fields for the low NAO period were adjusted by the regression coefficients obtained during the high-NAO period between NCEP and SOC atmospheric model fields. One success criterion for the high and low NAO simulations was to reproduce the high NAO vs. low NAO behavior of the Gulf Stream North Wall (GSNW) path, where the GSNW has been observed to be further north of its mean position during high NAO years and conversely, seen to be further south during low NAO years. Fields from high and low NAO simulations are used to determine the mean position of the GS from  $75\text{--}45^\circ\text{W}$ . The GS mean position estimation is done by initially obtaining the positions of the GS at depths of 50 m, 100 m, 200 m and 400 m by following the  $17^\circ, 16^\circ, 15^\circ$  and  $12^\circ$  isotherms, respectively, at 3-day intervals. The respective isotherms are subsequently integrated over depth and averaged annually for low and high NAO simulations to obtain the respective mean GS position. The mean GS position is observed to be northward (southward) during high (low) phases, in agreement with previous work by Taylor and Stephens (1998) and Taylor and Gangopadhyay (2001). See **Figure 5**.



**Figure 5:** Annual upper layer-integrated (50-450 m) Gulf Stream positions for high (red) and low (blue) NAO simulations.

The southwestward extent of the Labrador Current is known to vary with the NAO. We use the density of the Labrador Current at 100 m as a conservative tracer for the estimating the Labrador Current inflow into the western North Atlantic. The density is estimated from model-derived temperature and salinity fields obtained from high and low NAO simulations. Annual mean density estimates for high and low NAO simulations exhibit larger inflow of denser Labrador Current water [27.4] during low NAO years. **Figure 6** shows the progression of modeled Labrador Sea Water during 1995-1998.



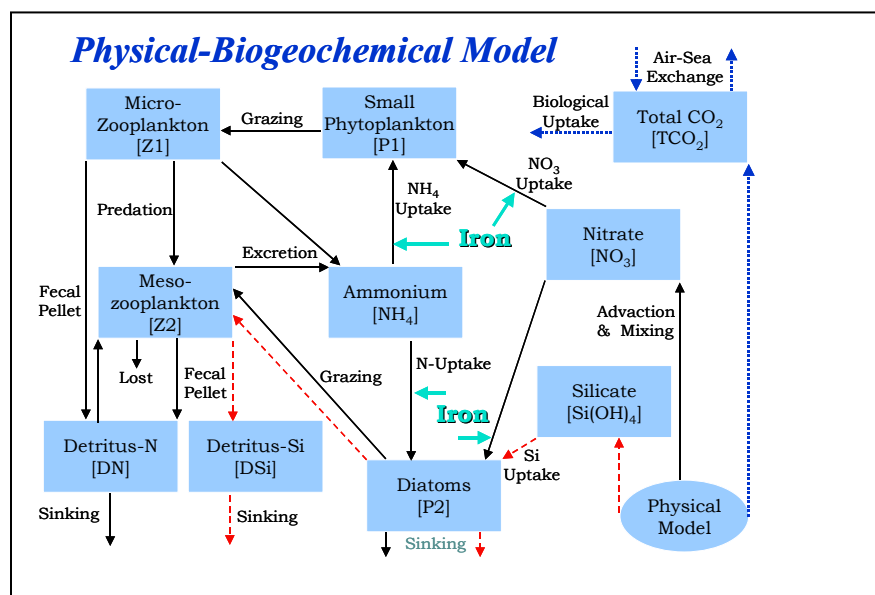
**Figure 6.** This four-panel figure shows the density signatures for the month of July during the four years of GLOBEC period in the present model simulation. The yellow region corresponds to the LSW density range of 27.2 through 27.4  $\sigma_\theta$ . Bluish waters are lighter, and redder waters are heavier than LSW. Two effects are apparent: (i) the advection of LSW in the WNA from 1995 (top-left) through 1998 (bottom-right); (ii) the advection of the North Atlantic Current into the Nordic seas in 1997 (bottom-left) and 1998. Both of these effects are due to the large drop of the NAO index during 1996. The three-gyre system in this region is also distinguishable in the 1996 panel, while its inter-gyre interaction and possible reconfigurations are indicated in the other years.

### 2.3 Ecosystems Modeling

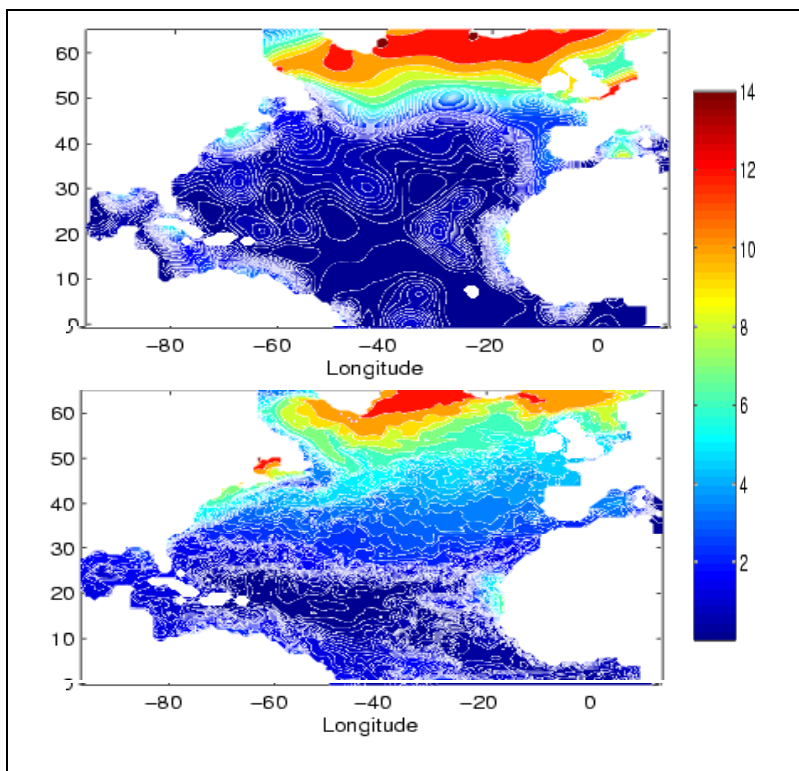
We will simulate North Atlantic ecosystem dynamics using the CoSINE (Carbon, Si(OH)<sub>4</sub>, Nitrogen Ecosystem) ecosystem model (**Figure 7**) developed through a collaboration between Drs. Chai and Dugdale (Chai *et al.*, 2002; Dugdale *et al.*, 2002). CoSINE includes silicate, nitrate and ammonium, two phytoplankton groups, two zooplankton grazers, two detrital pools, and TCO<sub>2</sub>. Recently, oxygen has been added to constrain remineralization processes in the model. Below the euphotic zone, sinking organic matter is converted to inorganic nutrients by a regeneration process similar to one used by Chai *et al.* (1996), where organic matter decays to ammonium and then is nitrified to NO<sub>3</sub>. CoSINE has been used in the North Pacific (Chai *et al.*, 2003) and the equatorial Pacific (Jiang *et al.*, 2003; Jiang and Chai, 2005). The carbon fluxes and other physical and biological variables from the CoSINE model have been incorporated into a recent inter-model comparison study for the North Pacific (McKinley *et al.*, 2006).

Dr. Chai has been funded to collaborate with colleagues from JPL/NASA, NRL and LANL to incorporate CoSINE and other comparable ecosystem models into ROMS and other circulation models (NCOM and

POP) for various regions, such as the Pacific Ocean, Peru Coast and California Current System. Our preliminary 3/4° ROMS integration included an earlier version of CoSINE and was able to capture essential biological features in the North Atlantic (**Figure 8**).



**Figure 7.** Schematic diagram of the CoSINE biogeochemical ecosystem model to be used in the proposed modeling activities over the North Atlantic basin. Black arrows show the path of N; dashed red arrows show the path of Si; and dotted blue arrows show the path of CO<sub>2</sub>. Indicated points show uptakes that are a function of iron availability.



**Figure 8:** Surface nitrate (mmol Nm<sup>-3</sup>) concentration for the winter season from observations (upper panel) and our coupled physical (ROMS)-ecosystem simulation (lower panel). The observations derive from NODC climatology, while the model results are an average of five model years. The high concentrations of nitrate are located in the subpolar gyre.

### 3. Ecosystem Response to Long-term Variability in Freshwater Input

Studies of the response of ocean primary productivity to climate variability and change have tended to emphasize the influence of surface heating and wind. Behrenfeld *et al.* (2006) found a strong negative correlation between total primary productivity and warming and concluded that warming, by increasing stratification, leads to reduced production at low and mid latitudes. Ueyama and Monger (2005) identified wind mixing as the dominant process controlling interannual variability in timing of the spring bloom in the North Atlantic. Dutkiewicz *et al.* (2001) argue that in stratified areas, *e.g.* the subtropics, but also temperate regions during summer, increased mixing would lead to an increase in primary productivity by reducing nutrient limitation; while in well mixed areas, *e.g.* subpolar regions, but also temperate regions during winter, increased mixing will reduce primary productivity through enhanced light limitation.

The findings underscore the importance of plankton community dynamics, as modulated by changes in stratification, mixing, circulation and nutrient transport, in controlling zooplankton and higher trophic levels over interannual and decadal time-scales. However, relative to wind forcing and heating, changes in direct hydrologic forcing -- including precipitation-evaporation and freshwater inputs from rivers and ice melt -- have received less attention as possible drivers of variability in phytoplankton dynamics.

#### 3.1 Research questions

The decade of 1990-1999 witnessed a sustained period of high-NAO conditions, followed by the largest drop to a low-NAO condition in 1996, and alternating low and high periods to end the century. Major changes in sea-ice melt and formation have resulted in huge freshwater input to both ENA and WNA regions. Throughout the 1990s, the NW Atlantic Shelf experienced persistent freshening, likely associated with increase ice export from the Arctic (Greene and Pershing 2007). The freshening was associated with increased phytoplankton abundance in the Gulf of Maine (Greene and Pershing 2007) and Newfoundland Shelf (de Young *et al.* 2004). In both regions, the phytoplankton changes resulted in increases in zooplankton (Pershing *et al.* 2005; Sheridan and Landry 2004).

We focus our studies on the decade 1990-1999, and the ensuing two decades, to consider the consequences of the observed, and projected, hydrologic changes. In particular, we will conduct a linked series of retrospective and future coupled simulations (see section 3.2) to address the following questions:

##### Question # 1 (Q1)

**“Are the biophysical environments which sustain the populations of *Calanus finmarchicus* in the three gyres (WNA, NNA and NOR) of the North Atlantic connected to one another, and by what pathways and processes?”**

- Are the **nutrient and phytoplankton dynamics in these three gyres** independent from one another (or not)?
- What are the **exchange rates** among the three gyres, and do they control plankton dispersal across the North Atlantic Ocean?

##### Question # 2 (Q2)

**“How significant is freshwater variability in determining the stratification and its subsequent impacts on primary productivity in the northern North Atlantic?”**

- What are the **relative roles of freshwater inputs** compared with other local influences on stratification and mixing (e.g., E-P, heating/cooling, winds, etc.)?
- Are the ecosystem impacts of hydrologic variability related to **large-scale changes in circulation patterns** and the transports of the various North Atlantic current systems, which make up the different boundaries of the three-gyre system?
- What **future changes** are expected based upon IPCC projections of climate change?

### 3.2 General Approaches

We propose to carry out a set of eddy-resolving basin-scale and regional model simulations, analyze satellite and other available data sets from the GLOBEC period, validate the model simulations, and use the simulations to address questions **Q1** and **Q2**. Our approaches are based on (i) simulating selected events during the last decade (1990-1999) with the eddy-resolving ROMS basin-scale model; (ii) validating these simulations with a new assemblage of hydrographic data and the synthesis study for the decade by Hakkinen and Rhines (2004); (iii) simulating high-resolution physical and biological fields for a nested domain encompassing the three-gyre distribution of *Calanus finmarchicus* using a combination of ROMS and CoSINE; and (iv) forecasting 20 years of North Atlantic Ocean using idealized forcing fields based on IPCC scenarios. In addition, we will (v) provide the basin-scale and high-resolution simulation fields for forcing other regional models (both physical and biophysical) and specifically to the Greene *et al.* proposal team for synthesis with their data-based retrospective analyses.

### 3.3 Proposed Modeling Effort

We propose to reconfigure or implement two model domains. The **North Atlantic Basin (NAB)** model will cover from 30S to 80N and from 80W to 30E; will incorporate 50 vertical levels (similar to those in Phase IVB) and will have 10 km horizontal resolution. The other, called the **Sub-Polar North Atlantic (SPNA)** domain will have a 3-5 km horizontal grid, comparable vertical resolution, and will cover the three-gyre plankton distribution (25-75N, 80W-30E). The SPNA domain will be nested within the NAB domain and will be linked with the 10-component lower trophic sub-model.

The rationale for the nested model is to more accurately study dynamic-hydrologic connections over the northern NAB. The proximity of the northern North Atlantic to the Arctic region must influence the *Calanus* behavior of the Northernmost gyres. For example, the impact of sea-ice melt influences the timing of the phytoplankton bloom and subsequent *Calanus* growth (ESSAS report, 2004). The lower trophic sub-model, employed at the higher resolution of the SPNA domain, will be used to explicitly represent the biophysical environment that ultimately affects the *Calanus* distribution and dynamics.

Three related sets of tasks are envisioned. Personnel responsibilities for these tasks are discussed below.

#### 3.3.1 Model formulation and implementation

During the first four months, Rutgers and UMass will jointly (i) reconfigure the NAB model for its enhanced domain size and inclusion of riverine inputs and sea ice; (ii) develop the singly nested SPNA ROMS with linked CoSINE sub-model; and (iii) introduce freshwater forcing variability via the open boundary condition options within ROMS.

Most shallow regions of the Sub-Arctic Seas experience seasonal sea ice, although the duration and severity of ice is spatially dependent (See Fig. 7 of ESSAS Report, 2004). In winter, relatively heavy ice is observed in the northern Bering Sea, the Sea of Okhotsk, the northern Barents Sea, Hudson Bay and on

the Labrador and northeast Newfoundland shelves. The duration of sea ice can extend upwards to 8-10 months in the northern parts of these regions. During the winter season, ice generally begins to form first in the north, and spreads by a combination of ice transport and local formation. The maximum ice coverage usually occurs in March or April. The Budgell (2005) sea ice model has already been coupled with ROMS and shown excellent agreement in the Barents Sea; it will be used here in both the NAB and SPNA domains. We will use the SSM/I product from NSIDC (national snow and ice data center) for ice coverage and ice velocity for the 1990-1999 period.

For rivers, we will implement them as point sources of freshwater input during the 1990-99 period for major rivers in the Atlantic Basin. At a minimum, they would include the Amazon, the Orinoco, the Mississippi, Rio Grande, the US East Coast Rivers, Rivers flowing into the Gulf of Maine, the Nelson, St Lawrence, the Norwegian Sea rivers, the Barents sea rivers, Mediterranean Outflow, and the Congo river. Some of the fields are available from the TRIP (Total Runoff Integrated Pathways) data set which can be found at <http://hydro.iis.u-tokyo.ac.jp/~taikan/TRIPDATA/TRIPDATA.html>.

The other forcing fields, such as the E-P, the heat flux and the wind stress fields for the 1990-1999 fields will be generated by using the forcing field adjustment technique developed in the P4B project discussed before on the daily available NCEP reanalysis fields.

### 3.3.2 Simulation and Validation

During the second phase (Months 4-20), the team (UMass+RU+UMaine) will (i) run the NAB model for 1990-1999 with sea ice and rivers; (ii) compare this run with the existing Phase IVB run for both ENA and WNA; (iii) run the SPNA nested domain with active biogeochemistry; and (iv) validate the property fields in the SPNA while addressing biophysical subsets of Q1 and Q2. Specifically:

We will derive the initial and boundary conditions for the ROMS North Atlantic basin model from SODA 2.0.3 (0.4 degree Simple Ocean Data Assimilation; Carton *et al.*, 2000a, b). This global retrospective analysis of upper ocean temperature, salinity and currents is available for 46-years (1958-1999). SODA used the GFDL MOM2 physics and assimilated data from the World Ocean Atlas-94 from MBT, XBT, CTD and station data, additional hydrography, SST and altimeter datasets. The NAB simulation will be initiated in 1985, and “spun up” for 5 years.

We will force the contemporary model simulations using the adjusted NCEP fields and realistic sea ice and riverine flow fields for the 1990-1999 period. This first run, covering the entire North Atlantic Basin, will not include biology and its results will be compared with the existing results of our Phase IVB simulation for the WNA and ENA (*e.g.*, Figure 5). Greene and Pershing (2007) showed that the 90-92 event was driven by Arctic freshwater and conjectured that such might be the case for 96-98 event. Increasing freshwater input would have caused increase primary productivity in the WNA, which resulted in the increasing *Calanus* population in the 1990's. Our existing Phase IVB simulation shows the LSW advection with ROMS for 96-98 period (see Fig. 5), reasonably captured without ice or rivers (*i.e.*, with heat flux and NAO winds only). With the proposed simulations, incorporating freshwater fluxes, we will be able to extend the Greene *et al* analysis to include multiple physical forcing effects and events during both 90-92 and 96-98.

The SPNA simulation will be initialized with the state of the NAB simulation in 1987, spun up for three years, then run for the decade of the 1990's using identical surface forcing as that used in the NAB simulation. The 10-component CoSINE model will be started from climatological biological conditions within the SPNA domain. We will validate the biological variables against available observations during the 1990's from GLOBEC and other programs. From the ten-year CoSINE simulation, we will be able to

establish spatial patterns and distribution of nutrients and primary productivity for each of the three gyres, and to compare and contrast them to address Q1 and Q2.

In the ENA, low-NAO driving during 1996-97 produced dry periods ( $E-P > 0$ ) and resulted in salinity increase in the Norwegian Sea. There is some indication of this happening in the Phase IVB simulation (see Figure 5). Increasing salinity in the ENA might enhance vertical mixing, which might lead to light limitation. However, increasing surface heat flux will increase primary productivity, which could balance the effects of salinity increase. We will quantify these balances with the proposed SPNA simulation.

One of the major validation data sets for the simulations for the NAB will be the recently compiled salinity dataset. Under Dr. Bisagni's (UMassD) direction, all hydrographic data from Bedford Institute of Oceanography's "Climate" hydrographic database, along with extensive Russian data from a NOAA-funded data-rescue effort were recently combined and quality-controlled to produce a regional data set for the western North Atlantic Ocean. This combined data set contains over 500,000 temperature and salinity data pairs at standard depths to produce a global data set from which shelf water volumes will be calculated using the definition of shelf water as water with salinity less than 34 PSU as described by Mountain (1991). All hydrographic data will be partitioned spatially into approximately 10 distinct regions or "boxes" from the Tail of the Grand Banks to Cape Hatteras. The area within each region will be apportioned among the stations occupying each region using the inverse square technique of Mountain (2003). Thus, the thickness of shelf water at any given station multiplied by its apportioned area represents the volume of shelf water assigned for that given station. Summing over all stations within each area will determine the overall volume of shelf water for each region. For each station, the average shelf water temperature and salinity will also be calculated. Multiplying the average temperature and salinity by the volume for each station, summing over all stations within a region, and finally dividing by the total shelf water volume in each region will produce the volume-weighted temperature and salinity for the region. Additional procedures to normalize the shelf water volume for differing station coverage for each survey are described by Mountain (2003).

Another validation data set is available from the University of Bergen (courtesy, Jan-Kristian Jensen of IFF, a PhD student of Dr. Gangopadhyay). All available data for the Eastern North Atlantic are combined to produce a regional data set for this region. Of particular value is the data from the weather ship "Station M" ("Station Mike") at 66N, 2E, provided by the University of Bergen, Norway, and hydrographic stations at fixed locations done by the Institute of Marine Research, Norway (IMR). From Station M there is an almost unbroken time series of weekly water samples from 1948 until today (Nilsen, 2003; Nilsen and Falck, 2006), making it the world's longest continuously time series of deep ocean measurements. IMR hydrographic stations are synoptic transects (cross sections) done at semi-regular intervals, typically 1 to 12 times annually. Station M is situated on top of the northernmost branch of the NE Atlantic current. Together with the "Svinoy" cross section from IMR (which crosses the two branches of the NE Atlantic current south of Station M), there is sufficient observational data to assess the variations and trends of the Atlantic inflow to the NE Atlantic.

Lastly, we may investigate connectivity in the three gyres from a Lagrangian point of view using the passive float capability in ROMS. We will seed representative particles at preferred Calanus depths (from observations) in the three systems to infer their aggregate trajectories. As an extension of this technique, we will test whether the gyre exchange is dominated by mean flow or eddies from the high-resolution simulation.

### **3.3.3 Future scenarios of change**

During the last phase (Months 13-24), our team will consider future changes in ecosystem behavior spanning the next two decades across the northern North Atlantic Ocean. We will conduct several

representative simulations using the SPNA nested model. These will be **forecast studies based upon IPCC scenarios** with a focus on the relative roles of changes in surface forcing and in freshwater inputs (*e.g.*, increases in Arctic exports of fresh water).

The IPCC uses a suite of models and examines multiple emission scenarios. We plan to use the output from the Geophysical Fluid Dynamics Laboratory (GFDL) climate model which has one of the more skillful representations of current climate in the North Atlantic among the IPCC suite of models (IPCC AR4, 2007). We propose to force the SPNA model with the output of the GFDL climate model under three emissions scenarios: high (A1F1), medium (A1B) and low (B1). Consistent surface and hydrologic forcing will be applied to the SPNA. All simulations will be initialized in 2000, from the end state of our contemporary hindcasts, and be carried forward for 30 years using the combined ROMS-CoSINE model.

Of interest in these future scenarios will be the projected variability in circulation and hydrology of the northern North Atlantic, and the accompanying changes in nutrients and primary productivity. In particular, we will attempt to characterize future changes in the three-gyre circulation of the northern North Atlantic, its ecological implications, and how these are related, separately and in combination, to surface forcing and freshwater fluxes.

### **Intellectual Merit.**

This proposal seeks a synthetic understanding of how basin- and global-scales changes in climate force physical processes that in turn determine local- and regional-scale biological communities, with a particular focus on freshwater forcing of circulation, mixing, and marine ecosystems within the North Atlantic Ocean. It is pan-regional in scope, building upon the successes of the U.S. GLOBEC program in the Western North Atlantic (and its other regions) to address climate variability issues spanning the entire northern North Atlantic Ocean. Its research approaches include: synthesis of datasets across the North Atlantic, multi-scale coupled physical/biological modeling, and comparative regional studies. In all these respects it responds directly to the U.S. GLOBEC Pan-Regional Synthesis Announcement of Opportunity.

### **Broader Impacts.**

Two graduate students will participate in this project. Results will be disseminated by peer-reviewed scientific publications, presentations at national conferences, and to other Pan-Regional GLOBEC investigators (*e.g.*, Greene and colleagues). We will make the model output available via the Rutgers OPeNDAP server. We will give public lectures in Schools of Massachusetts, Maine and New Jersey on the importance of NAO and its impact on the regional ecosystem as part of our ongoing K-12 outreach program. The forecast scenarios for the next two decades will increase awareness of Climate Change. Note that Dr. Fei Chai is a New Investigator to the GLOBEC program and will bring considerable expertise from his associations in the Pacific and in the Climate Change communities. Finally, this project sets the stage for post-GLOBEC end-to-end studies in the North Atlantic (*e.g.*, the BASIN program).

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