PROJECT DESCRIPTION

1. Prior NSF Support

OCE-0452743, $183,759 (University of Colorado portion). *Collaborative Research: Dynamics of Ocean Climate Changes in the Gulf of Alaska*. **A. Capotondi**, M. A. Alexander, A. J. Miller, E. Di Lorenzo, 3/1/2005-2/29/2008. We have investigated the dynamical processes underlying low-frequency variability in the Gulf of Alaska over a broad range of timescales, from seasonal to interdecadal. Simulations with a regional eddy-permitting ocean model forced with observed wind fields over the period 1950-2004 shows that sea surface height (SSH) variations at interannual and decadal timescales, as well as eddy statistics in the eastern basin, are significantly correlated with the ENSO and PDO indices (Combes and Di Lorenzo 2007). The results from the eddy-permitting ocean model confirm previous findings obtained with a coarse resolution model in that a large fraction of SSH and pycnocline variability (and Alaska Gyre strength) is driven by local Ekman pumping in the central and eastern part of the Gulf of Alaska, while pycnocline and SSH changes are communicated to the western basin through advection or coastal wave propagation (Capotondi et al. in preparation). Analysis of an ocean model coupled to a biological model showed that the shoaling of the pycnocline in the central Gulf of Alaska after the 1976-77 climate regime shift resulted in a shallower mixed layer depth and a change in the seasonality of biological processes (Alexander et al. in press).

NA Bond: NSF ATM 0240784, $103,438.00 (University of Washington component), 1 May 03 - 30 Apr 06. *Collaborative Research: Barrier Jets – Causes, Impacts and Interactions with other Phenomena.*
This project consisted of a modeling and observational study of the structure and dynamics of barrier jets in the Gulf of Alaska; the PI coordinated the field component involving a research aircraft. Journal articles have been published (listed in References) on the frequency and spatial distribution of barrier jets along the Alaskan coast (Winstead et al. 2006), turbulence distributions in a downslope windstorm (Bond et al. 2006), and a type of barrier jet that involves interactions with gap flow (Olson et al. 2007).

NSF OCE 0627247, $70,918.00 (University of Washington component), 15 May 06 – 30 Apr 09. *US-GLOBEC NEP Phase IIIb-CGOA Environmental Influences on Growth and Survival of Southeast Alaska Coho Salmon in Contrast with Other Northeast Pacific Regions.*
This project involves a combination of retrospective and field work related to coho salmon and their habitat. The PI is taking the lead on characterizing the regional oceanographic conditions encountered by the salmon and relating those conditions to climate-scale variability. The early results indicate the adult returns from individual stocks exhibit less coherent fluctuations than originally supposed, and that these returns are more controlled by predation than food availability (LaCroix et al. 2008). In general, the quality of the habitat for these salmon does not appear to be simply related to the basin-scale climate.

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), Collaborative Research: US-GLOBEC NEP Phase IIIa-CCS: Effects of Meso- and Basin-Scale Variability on Zooplankton Populations in the CCS Using Data-Assimilative, Physical/Ecosystem Models : (OCE-0435592, $182,000, 2005-2008) : Under this grant awards, Curchitser and colleagues 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 Curchitser *et al.* (2005), Powell *et al.* (2007), Huang et al. (2007), Fiechter et al. (2007), Hermann et al. (2007). Data from these simulations has been provided for use in many other regional modeling studies (*e.g.,* Gan *et al.*, 2006). Over 70 presentations have been given by the PIs at conferences, workshops and schools on various aspects of this work. Some of the output is viewable through a Live Access Server: http://ferret.pmel.noaa.gov/FOCI/servlets/dataset.

2. Introduction

While marine ecosystems are affected by local physical conditions, including upwelling, mixed layer depth, water mass structure, and light availability, there is a gathering body of evidence that local processes are influenced by large-scale climate variations. For example, decadal fluctuations in North Pacific salmon population are coherent with changes in the Aleutian Low pressure system (Beamish and Bouillon 1993) and the Pacific Decadal Oscillation (PDO; Mantua et al. 1997), the principal component of the leading pattern of sea surface temperature (SST) variability north of 20°N in the Pacific. The rapid transition of the PDO in the mid-1970s had a large impact on the whole Pacific including the west coast of North America (Trenberth 1990, Graham 1994, Miller et al. 1994, Hare and Francis 1995, Hare and Mantua 2000, Benson and Trites 2002). In the Atlantic, cod populations in the North Sea appears to fluctuate in phase with the North Atlantic Oscillation (NAO, Lehodey et al. 2006, and references therein)), a natural mode of variability consisting of a dipole in sea level pressure (SLP) between iceland and the Azores (van Loon and Rogers 1978, Rogers 1984). In the Southern Ocean, changes in ice conditions associated with large-scale variations of atmospheric forcing and ocean advection can have large impacts upon ecosystems ranging from phytoplankton to top predators, as exemplified by the biological changes observed in the West Antarctic Peninsula from September 2001 to February 2002 (Massom et al 2006). These biological changes resulted from anomalous atmospheric conditions associated with the Southern Annular Mode (SAM), the dominant pattern of atmospheric variability in the Southern Hemisphere (Fyfe et al. 1999, Kidson 1999, Thompson and Wallace 2000, Hall and Visbeck 2002, Raphael 2003).

A primary way by which large-scale climate forcing can impact ecosystems is by wind-driven changes in ocean circulation. Ocean currents advect water properties (e.g. temperature and salinity) as well as nutrients, and in some regions affect eddy variance, stratification and upwelling. Thus, natural and anthropogenic variability of the wind-driven ocean circulation is fundamental for understanding and predicting the evolution of marine ecosystems, including their response to climate change.

The primary approach for examining climate change is through simulations of general circulation models with increasing levels of greenhouse gases. Several modeling centers around the world have recently completed a large set of simulations in support of the Intergovernmental Panel for Climate Change (IPCC) Assessment report 4 (AR4). The IPCC AR4 models include atmosphere, ocean, sea ice and land components, which are fully coupled so interactions between the different components are explicitly modeled. The IPCC-AR4 simulations include both long control simulations (levels of greenhouse gases, solar input, and other external forcing are held constant), which provide a characterization of natural variability, as well as simulations of the 20th century, which were driven with variations in sulfates, solar input, volcanoes, ozone, a number of greenhouse gases, halocarbons and black carbon that are based upon the observed record and offline chemical transport models. These simulations were continued into the 21st century under different scenarios for the increase of greenhouse gases, based upon the Special Report on Emission Scenarios (SRES, Houghton et al. 2001). The output from these simulations, archived by the Program for Climate Model Diagnosis and Intercomparison (PCMDI, Meehl et al. 2007), have been used to examine a wide array of issues (e.g. see Chapter 8 of the IPCC report, 2007). The IPCC-AR4 models contain a fairly complete set of monthly-mean atmospheric and oceanic fields allowing us to examine the causes of climate variations and change over globe.

In this study we will use the IPCC-AR4 archive to examine the influence of climate variability and change upon the large-scale ocean circulation that influences the three regions studied within the US GLOBEC program: northeast Pacific (Gulf of Alaska/ California current system), northwest Atlantic, and Southern Ocean. Since climate models used in the AR$ assessment have insufficient resolution to simulate small-scale processes, we will focus upon the large-scale aspects of the ocean circulation that are known to be relevant for ecosystems in the GLOBEC regions. Statistical downscaling techniques will then be developed and tested using available observations and output from a regional model hindcast. These techniques provide a means to utilize the relatively coarse-resolution output from climate models to derive information about quantities relevant to ecosystems at a regional scale.

2.1 Northeast Pacific

Upon reaching the North American coast, the North Pacific current (NPC) bifurcates contributing to the southward flowing California Current and the northward Alaska Current.

Gulf of Alaska

The Alaska Current becomes narrower and stronger close to the apex of the Gulf and continues southwestward along the Alaska Peninsula as the Alaskan Stream. The circulation is approximately in geostrophic balance with the horizontal density gradients (Combes and Di Lorenzo 2007), so that the pycnocline has a doming structure, shallower in the central part of the Gyre, and deeper along the coast. A thick layer of low salinity surface waters covers most of the GOA. Since at low temperatures salinity has a dominant control upon density, the halocline, the depth with the largest salinity gradients determines the pycnocline. In winter, the mixed layer reaches to the top of the pycnocline (Freeland et al. 1997, Alexander et al. 2008), and the pycnocline depth is a good proxy for mixed layer depth (MLD). Thus, changes in the strength of the Alaska Gyre, and associated changes in the doming structure of the pycnocline can provide information about MLD changes. MLD regulates the amount of light and nutrients in the surface layer, the former has been shown to be important for primary production and the pelagic ecosystem in the GOA (e.g., Polovina et al. 1995, Alexander et al. 2008).

Interannual and decadal variations of the Aleutian Low and the associated near-surface winds affect the circulation in the Gulf of Alaska. From the late 1970s to the late 1990s, the cyclonic winds over the GOA were stronger relative to the pre-1976 period. As a consequence, the pycnocline shoals in the central part of the Gulf of Alaska, and deepens along the coast resulting in a more energetic gyre circulation. Figure 1 shows the changes in pycnocline depth associated with the 1976-77 climate shift (when the PDO changed from a negative to a positive phase), from both a coarse (IPCC-class) and a high-resolution model. Both models show a more pronounced doming of the pycnocline, and intensified Gyre circulation, and they both reproduce the variations in pycnocline depth measured at two stations in the Gulf of Alaska, Ocean Weather station Papa (50°N, 145°W), and station GAK1 (59°N, 149°W) (Figure 2). The pycnocline depth changes in the center of the Alaska Gyre and along the eastern part of the Gulf are primarily driven by the local manifestation of the large-scale wind forcing (Lagerloef 1995, Qiu 2002. Cummins and Lagerloef 2002, Capotondi et al. 2005). In contrast, the increased downwelling in the western part of the GoA are established by coastal propagation of pycnocline depth anomalies (Capotondi et al. 2005) either by ocean advection or coastal waves, where the latter are of both regional and equatorial origin (Meyers and Basu 1999).

While pycnocline/mixed layer depth can affect the intensity and of primary productivity in the center of the Gulf, mesoscale anticyclonic eddies are considered the primary source of nutrients for the offshore coastal regions, by entraining waters rich in iron near the coast and transporting it offshore (Crawford et al. 2008). Together with the relaxation of coastal downwelling, eddies also play a fundamental role in the transport of nitrogen from the deep basin to coastal waters (Ladd et al. 2005). In the eastern side of the Gulf of Alaska eddies tend to form as a result of instabilities along the continental slope, so that the frequency of these eddies is largely associated with the intensity of the large-scale circulation. For example, Crawford et al. (2002) report that the area occupied by eddies was anomalously large during the 1997 El Niño, when the circulation was stronger. The standard deviation of sea surface height (SSH) from an eddy-permitting ocean model also intensifies after 1976-77 in the eastern part of the Gulf. On the western side of the Gulf, on the other hand, eddies appear to be of intrinsic origin, and not significantly correlated with the large-scale forcing. (Okkonen et al. 2001, Combes and Di Lorenzo 2007). Thus, understanding the variability of the Alaska Gyre and its connection with the atmospheric forcing can provide important information about MLD, fluctuations in coastal downwelling, as well as eddy statistics on the eastern side of the basin.

California Current System (CCS)

The wind-driven California current system (CCS) advects cold water southward along the western coast, thus contributing to a significant land-sea temperature and pressure difference in spring-summer when the land warms. This pressure difference results in northerly coastal winds that drive coastal upwelling, bringing nutrient rich water to the surface. The California Current is also linked to the large-scale wind forcing and ocean circulation. For example, the second EOF of SST and sea surface height (SSH) over the North Pacific is characterized by a dipole-like structure with a nodal line along 40°N, close to the axis of the eastward flowing NPC. Variations of this mode primarily correspond to a strengthening and weakening of the north Pacific gyre circulation. The associated principal component, termed the North Pacific Gyre Oscillation, or NPGO, by Di Lorenzo et al. (2007) shows a statistically significant correlations with variations of sea surface salinity (SSS) and Chlorophyll-a (Chl-a) in the CCS. Both SSS and Chl.-a are quantities that are strongly correlated with the alongshore wind and coastal upwelling (DI Lorenzo et al. 2007). Fluctuations in the NPGO may also link changes in the CCS and the GOA.

North of Cape Mendocino (~40°N) upwelling starts in spring and lasts until fall, while south of Cape Mendocino upwelling occurs year-round. The seasonality of upwelling in the northern region appears to be crucial for ecosystem dynamics, especially for species whose life history is closely tied to the seasonal cycle. For example, a delayed upwelling in the spring of 2005 appeared to be the cause of anomalous conditions in the CCS, with warmer than average SSTs, low biological productivity, spatial redistribution of some zooplankton species, and the breeding failure of some planktivorous marine birds (Schwing et al. 2006).

The rising of land temperatures due to global warming can be expected to lead to increased land-sea pressure gradients (since continents are projected to warm much faster than the adjacent ocean), enhanced alongshore winds, and increased coastal upwelling. This lead Bakun (1990) to hypothesize that coastal upwelling and CCS productivity will increase as a result of global warming. This hypothesis is supported by observations of an increasing upwelling trend (Schwing and Mendelssohn 1997, Mendelssohn and Schwing 2002, Diffenbaugh et al. 2004) in the CCS. Sensitivity experiments performed with a regional atmospheric model forced with fixed SSTs that were in equilibrium with the pCO_2 concentration showed that increased CO_2

levels affect the magnitude and seasonality of the coastal wind stress curl, and upwelling, by causing an increase in the sea-land temperature gradient (Snyder et al. 2003). This study did not include ocean-atmosphere feedbacks due to the lack of a dynamical ocean. Thus, the influence of global warming upon coastal upwelling bears investigating using fully coupled climate models. Some preliminary work on this topic (Wang et al. 2008) suggests that the models may have difficulty capturing the local pressure gradients that drive the along-shore winds, and correctly reproduce its seasonality. On the other hand, Schwing et al. (2006) showed that the variability in the upwelling in the CCS is linked to large-scale pressure patterns, which we expect to be relatively reliably forecast by the IPCC-AR4 models, and could be used to infer coastal upwelling. Several factors may impact the large-scale flow in the North East Pacific as a result of global warming including changes in coastally-trapped ocean waves, the duration, location and strength of internal fluctuations in the Aleutian Low, atmospheric teleconnections associated with SST anomalies in the tropical Pacific (Alexander et al. 2002, Miller et al. 2004, Schneider and Cornuelle, 2005, Deser et al. 2008) and possibly the atmospheric response to reduced sea ice in the Arctic (Sewall and Sloan 2004, Seawall 2005*)*.

Apart from influencing upwelling, advective processes have a large impact upon the water mass composition along the California/Oregon coast, which in turn, influence zooplankton biodiversity (Hoof and Peterson 2006). Zooplankton composition undergoes seasonal variations which are linked to the wind-driven upwelling dynamics: during winter, the weak upwelling season, the northward flow of the Davidson current brings subtropical fauna, characterized by higher biodiversity, to the Pacific Northwest, while during the summer months, when upwelling is strong, increased transport of northern subarctic waters leads to a dominance of low-diversity subarctic species. The relative strength of northward vs. southward transport along the northern California/Oregon coasts affect biodiversity also at interannual to decadal timescales. Northward transport of downwelling Kelvin waves during El Niño events (Lynn and Bograd 2002) leads to a larger biodiversity along the coast of the Pacific Northwest. Significant correlations are also found with basin-scale indices (e.g. PDO), while no clear connection appear to exist with indices of local wind forcing. Thus, large-scale atmospheric forcing and ocean dynamics are key factors in the zooplankton composition and abundance in this region.

2.2 Northwest Atlantic

Several studies have shown the existence of pronounced interannual and decadal variability in the upper-ocean temperature and salinity of the northwest Atlantic (Levitus, 1989, Deser and Blackmon 1993, Kushnir 1994, Reverdin et al. 1997) and ocean circulation changes have been emphasized as a contributing cause of those low-frequency variations (Petrie and Drinkwater 1993, Battisti et al. 1995, Sutton and Allen 1997, among others).

A prominent aspect of the northwest Atlantic ocean circulation is the slope water system south of Newfoundland. The slope water jet separates from the Gulf Stream between 60°W and 65°W and then flows eastward bringing warm and saline waters near shore. Further inshore there is the westward flowing Labrador Current (LC) carrying colder and fresher waters of Arctic origin. The two currents are separated by strong temperature and salinity fronts (Pickart et al. 1999). The slope-water system is characterized by interannual modes of variability that couple the surface flow with that of the deep western boundary current (DWBC) below 1500 m. The "maximal" modal state, as defined by Pickart et al. (1999) consists of a more pronounced Labrador Sea water (LSW) signature at depth, while the slope-water jet is weaker and displaced further offshore. Opposite conditions are found during the "minimal" modal state, where LSW is less ventilated, and the slope-water jet moves onshore. Oscillations between these two modes can significantly impact the temperature and salinity distribution in the coastal waters, and affect the seasonality and growth rates of phytoplankton and zooplankton. "Shifts" in the modal states of the slope-water system has been linked to the evolution of the NAO (Greene and Pershing 2007). Annual mean values of regional slope-water temperatures between 150 m and 250 m appear reasonably well correlated with the evolution of the NAO index (annual values) over the period 1960-2000. More specifically, changes in the sign of the NAO index are followed by similar shifts in slope-water temperatures 1-2 years later. For example, the shift in the NAO during 1976 was followed by a decrease in the slope-water temperature two years later, and a pronounced decrease in the abundance of *Calanus finmarchicus*, a copepod that dominates the springtime zooplankton biomass in the northwest Atlantic (Mauchline 1998).

What is the connection between NAO index and modal state in the northwest Atlantic? During high NAO years, enhanced buoyancy forcing over the Labrador Sea has been linked to increased LSW formation (Dickson et al. 1996). High values of the NAO are also associated with intensified westerlies, and intensified gyre circulation in the North Atlantic, which could influence the relative strengths of the slope-water jet and LC. The relative role of LSW formation and gyre circulation changes needs to be clarified. Observational and modeling studies (Petrie and Drinkwater 1993, Greatbatch et al. 1991, Loder et al. 2001, Marsh 2000) have emphasized the importance of changes in the LC transport for determining the temperature and salinity anomalies of the waters south of Newfoundland. The modeling study of Marsh (2000) showed that increases in the subpolar current transport around the Grand Bank and reduction of slope-water temperatures around Nova Scotia result from large-scale wind stress changes. Thus, variations in LC transport can be very critical for determining the temperature and salinity condition in the coastal water of the western North Atlantic. Changes in this transport may be partially driven by the large-scale atmospheric wind forcing possibly connected to NAO variability at decadal timescales.

Advection by ocean currents influences the variability of upper-ocean temperature and salinity not only because of changes in the strength of the currents, but also due to variations of the properties of the water mass being advected. The freshening observed in the northwestern Atlantic since the early 1990s has been attributed by some authors to advection of low-salinity waters of Arctic origin (Steele et al. 2004, Häkkinen 2002, Greene and Pershing 2007). Enhanced freshwater export from the Arctic either through the Fram Strait or the narrow, complex channels of the Canadian Archipelago may result from changes in the Arctic Ocean circulation forced by anomalous atmospheric conditions, ice melting, as well as increased river discharge (Holland et al. 2006a, and references therein). Decreased salinity in the coastal waters of the northwestern Atlantic results in increased stratification and enhanced phytoplankton production especially in the fall months when the mixed layer would normally deepen. Freshwater discharge from the Arctic is likely to increase due to the melting of sea ice associated with global warming.

2.3 Southern Ocean

Due to the absence of major continental boundaries, climate signals can be transmitted between ocean basin and remain coherent across all of the basins. In addition, since the SO ecosystem has short trophic linkages dominated by few species, climate variability and change can easily affect all ecosystem components. The mean atmospheric circulation in the SO is characterized by (quasi-) zonally symmetric westerly winds that drive a northward Ekman transport at all longitudes, creating a divergent flow away from the Antarctic continent and preventing warm subtropical water from reaching the circumpolar region. This results in the establishment of a strong temperature and density gradient that drives the intense easterly flow of the Antarctic Circumpolar Current (ACC), the major current of the SO. Thus, ocean circulation and wind forcing are strongly coupled in the SO (Hall and Visbeck 2002). The dominant mode of atmospheric variability in the SO at interannual-to-decadal timescales is the Southern Annular Mode (SAM,), defined as the leading EOF of SLP (Thompson and Wallace 2000). Other modes of variability that can affect the SO include ENSO (Carleton 2003, Turner 2004, Yuan 2004, among others), and the Antarctic Circumpolar Wave (White and Peterson 1996, Connolley 2003).

Positive changes in the SAM are associated with a poleward displacement of the westerly winds. Using a coarse-resolution ocean-atmosphere-ice model, Hall and Visbeck (2002) have shown that SAM-driven changes in ocean circulation include anomalous northward Ekman drift in the circumpolar region (where the westerlies intensify, south of ~45°S in the model) and southward (poleward) Ekman drift further north (where the westerlies weaken). Anomalous convergence and downwelling result around 45°S, while anomalous upwelling occurs close to the Antarctic continent. The northward flow in the circumpolar region is associated with northward heat flux, cooling and increased ice coverage close to the Antarctic continent (Hall and Visbeck 2002).

Over the past decades the SAM has exhibited a mostly positive trend (Kidson 1988, Karoly 1990, Hartmann and Lo 1998, Thompson et al. 2000). The strengthening of the circumpolar westerlies is associated with a southward displacement of the ACC (Fyfe and Saenko 2005), which may partly explain the observed SO warming at depths of 700-1100m between 45° and 65°S (Gille 2002). The latitude range where mid-depth ocean warming is observed is not fully consistent with the surface cooling found in the modeling study of Hall and Visbeck (2002) south of ~ 45°S. This inconsistency may be due to the simplicity of the model used by Hall and Visbeck (2002), and warrant further investigation with more complex climate models.

SAM variability appears to have a tremendous impact upon ocean properties and sea ice coverage around the Antarctic continent. These quantities, in turn, have a large influence upon the local ecosystem (Massom et al. 2006). The position of the ACC itself is of large ecological importance, as the southern boundary of the ACC, where nutrient-rich Upper Circumpolar Deep Water (UCDW) lies relatively close to the surface, corresponds to a region of large phytoplankton biomass and distribution of krill and whales (Tynan 1998), as well as elephant seals (Biuw et al., 2007). The ecological changes in the West Antarctic Peninsula associated with the pronounced warming trend experienced by that region over the last decade, has been recently reviewed by Ducklow et al. (2007).

3. Proposed work

We will focus upon the following questions**:**

1. Does the present generation of climate models show connections between large-scale low-frequency wind forcing variations and ocean circulation changes in the three GLOBEC study areas similar to those that we believe exist in nature? Can we use the IPCC-AR4 multi-model ensemble as long complete records thereby providing greater confidence in the statistical relationships between climate variability and ocean circulation changes?
2. Based on the most reliable models, will the influence of climate upon processes in the GLOBEC regions change in the next one to two centuries?
3. How successful can statistical downscaling be for relating variations at the regional (ecosystem) scale to large-scale climate forcing? Can we identify specific variables that are amenable to statistical downscaling?

While pursuing the above scientific objectives, we will closely collaborate with other groups that will examine the climate influences upon one or more of the GLOBEC regions from an observational, conceptual, and regional modeling perspective. Specifically, we can provide output from the IPCC models and guidance on how to use it to the researchers supported in the pan-regional phase of GLOBEC.

3.1 Analysis of the present-day climate simulations

We will start by examining simulations of the 20th century, as well as available long control simulations performed with the IPCC-AR4 models. A total of 23 models from 16 modeling centers and 11 countries around the world have participated in the IPCC-AR4, and have submitted simulations to the PCMDI archive (Meehl et al. 2007). These models differ in horizontal and vertical resolutions, as well as physical parameterizations for the unresolved sub-grid scale processes. For example, the Climate System Model version 3 (CCSM3) developed at the National Center for Atmospheric Research (NCAR) includes an atmospheric component that uses a T85 (~1.4°) resolution, with 26 vertical levels, and an ocean component with 1° horizontal resolution and 40 unevenly spaced (higher resolution close to the surface) levels in the vertical. The IPCC-AR4 models have already been extensive analyzed to assess their performance in reproducing basic aspects of the mean climate and some of the leading modes of climate variability (www-pcmdi.llnl.gov/ipcc/subproject_publications.php). We will make use of the results from previous studies to prioritize the models to be analyzed based on their performance.

The mean conditions of upper-ocean structure and circulation in the three GLOBEC regions as simulated by the control and 20th century runs will be examined and compared with available observations, ocean-only hindcasts (ocean-only simulations driven by observed forcing), as well as available ocean analyses (ocean simulations driven by observed forcing which also include surface and subsurface data assimilation; Carton et al. 2000a, b). Trends in forcing and ocean processes in the 20th century runs will also be diagnosed in relation to the control simulations to isolate anthropogenically-induced changes vs. natural variations. Finally, the leading modes of variability (ENSO, PDO, NPGO, NAO, SAM) will be examined. Because of the completeness of the model fields and the dynamical consistency among the different variables, the model output will allow not only to examine statistical relationships between climate forcing and ocean circulation, but also to investigate the dynamical processes responsible for those relationships. For example, heat budgets can easily be computed, and simple theoretical models (e.g. local Ekman pumping forcing, Rossby wave dynamics) can be tested, as in Capotondi et al. (2001, 2003, 2005).

Northeast Pacific

For each model, we will start by computing the two leading modes of monthly SST variability which represent the model rendition of the PDO and NPGO, and assess their spatial structure and spectral characteristics relative to observations. The time evolution of the PDO and NPGO indices will be compared with other indices of North Pacific variability. In particular, the North Pacific Index (NPI, Trenberth and Hurrell 1994), computed as the area-average sea level pressure (SLP) over the region 30°-65°N, 160°-140°W, and representing a measure of the strength of the wintertime atmospheric circulation over the North Pacific will be considered. Preliminary analyses of the PDO in future climates have already been carried out (Overland and Wang 2007, Wang et al. 2008). We will build upon these studies by extending our analyses to include the NPGO and NPI indices, and by examining the dynamical processes by which these modes of climate variability affect ocean circulation.

The North Pacific circulation changes associated with the variability of these modes will be first examined by using linear regression analysis. In the Alaska Gyre the evolution of pycnocline depth will be regressed upon the PDO and NPGO indices. Thus, the relative importance and interplay of these modes to describe the changes in the strength of the Alaska Gyre will be elucidated on the basis of model-produced, century long simulations. The evolution of the pycnocline and mixed layer depths, and the leading processes (Ekman pumping, advection, wave propagation) responsible for that evolution will then be examined as a function of season. Eddy statistics in the eastern part of the basin can be related to the strength of the Alaska Gyre, as a stronger Alaska Current leads to the generation of a larger number of eddies (Crawford et al. 2002), and to higher levels of SSH variability along the eastern coast (Capotondi et al. 2008, in prep.).

We will also examine the variations in the intensity of the NPC and of the branch that forms the California Current. The evolution of the current strength will be correlated with a coastal upwelling index, computed from the alongshore wind stress, as a function of season, using an approach similar to that adopted in observational studies (Bakun 1973, Schwing et al. 1996, Schwing et al. 2006), or derived from large-scale pressure patterns. Water mass properties (e.g. temperature and salinity) will also be diagnosed and correlated with the basin-scale climate indices, and currents strength. The focus will be on parameters known to be related to the ecosystem over a range of trophic levels (e.g., zooplankton, Mackas and Tsuda 1999; coho salmon, Logerwell et al. 2003). The relationship between GoA and CCS variability via the NPGO will be examined.

Northwest Atlantic

Given the importance of advection from the Labrador Sea toward the coastal areas of the western North Atlantic, we will examine the time evolution of the Labrador Current (LC) transport and its connection with the large-scale wind forcing at interannual and decadal timescales. The Ekman pumping anomalies over the North Atlantic will be regressed upon the low-passed time series of LC transport at a given latitude. The Ekman pumping outside the Tropics is proportional to the curl of the wind stress, and it is the driver of the gyre circulation. The LC transport will also be directly correlated with the NAO index to clarify the connection of the LC strength with the large-scale leading mode of North Atlantic variability. Time series of upper-ocean temperature and salinity along the model coastline south of Newfoundland will be compared with the LC transport further upstream, as well as with the transport of the Gulf Stream. Changes in LSW formation will be diagnosed from mixed layer depth changes in the models deep water formation site in the Labrador Sea (Holland et al. 2006a).

Following the modeling study of Holland et al. (2006a) the outflow from the Arctic through both Fram Strait and the Canadian Archipelago (Figure 3) will be computed and related to the component of atmospheric forcing that involves an east-west pressure gradient across the Straits. Changes in the water mass properties, especially salinity, of the outflows will be examined and correlated with the upper-ocean stratification in the Northwest Atlantic.

Southern Ocean

Several studies have already examined different aspects of Southern Hemisphere (SH) variability using the IPCC-AR4 data set (Carrill et al. 2005, Raphael and Holland 2005, Yin 2005, Fyfe and Saenko 2006, Russell et al. 2006). Although some biases are found in the simulation of the SAM in some models, the multi-model mean shows a SAM trend that is similar to the observed for the models in which ozone-depletion is included.

We will build upon these previous studies focusing on ocean and ice conditions that are of ecological relevance. More specifically we will examine winds, ocean currents, Ekman drift, oceanic heat transport, water properties (temperature and salinity) as a function of depth, as well as ice concentration and thickness, Most models have ice components that include both dynamical and thermodynamical processes, as well as an ice thickness distribution, so that different aspects of the ice can be diagnosed. Using the long control integrations we will examine the connection between SAM and ocean circulation using an approach similar to that applied by

Hall and Visbeck (2002). Given the strong zonal symmetry of the forcing, zonally averaged oceanic fields will first be considered. More in depth analyses of ocean and ice variations will be carried out in the area of the west Antarctic Peninsula, an area where the U.S. GLOBEC field program has been conducted, and which has been the focus of several observational studies due to its high climate sensitivity (King 1994, King and Harangozo 1998, Smith and Stammerjohn 2001, King and Comiso 2003, Massom et al. 2006). The influence of ENSO teleconnections upon variability around the Antarctic Peninsula will also be examined.

The 20th century simulations that include ozone-depletion will be used to examine the effect of the SAM trends on the ocean and ice condition in the area of the Antarctic Peninsula.

3.2 Climate Change Scenarios

Several different scenarios, corresponding to different levels of greenhouse gas emissions, have been considered (Meehl et al. 2007). They include 21st century simulations with SRES B1 scenario (low forcing, i.e. CO_2 concentration of about 550 ppm by 2100), SRES A1B scenario (medium forcing, i.e. CO_2 concentration of about 700 ppm by 2100), and SRES A2 (high forcing, with CO_2 concentration about 820 ppm by year 2100). The IPCC-AR4 archive also includes climate change commitment simulations for the A1B and B1 scenarios in which the CO_2 concentration is held at the year 2100 values and the simulations continued until year 2200. The multi-model means of surface warming for the different scenarios is shown in Figure 4. We will mainly focus upon the medium forcing case, SRES-A1B. Time permitting, some cases from the high-forcing and low-forcing scenarios will also be considered to address some of the uncertainties associated with the choice of future emissions.

For each of the three GLOBEC regions we will start by examining the mean conditions after the level of CO_2 has reached its maximum concentration (700 ppm) by considering the time average conditions over the 22nd century. In particular, we will examine the mean strength of the Alaska Gyre, upwelling in the CCS, as well as changes in the LC and Gulf Stream System with respect to the mean conditions of the 20th century. We will then proceed to examine the leading modes of variability (i.e. ENSO, PDO, NPGO, NAO, SAM) in a warmer climate. Are their spatial pattern, amplitude, and dominant timescales different after the end of next century? How do they impact the ocean circulation in the three GLOBEC regions? Analyses similar to those described in section 2.1 will be repeated to the commitment phase of the A1B scenario simulations. These analyses will be carried out on the subset of models that seemed to more realistically reproduce the links between climate forcing and circulation changes during the 20th century. Projections of mean conditions and variability may differ among models. For example, studies of ENSO in the IPCC-AR4 climate change simulations (Guilyardi et al. 2007) show very different projections for the amplitude and timescale of ENSO in the next century. We hope that by using several different models we can define a range of possible changes of climate forcing and ocean circulation.

Analyses of Arctic sea ice in IPCC-AR4 21st century simulations (Holland et al. 2006b) have shown the possibility of abrupt Arctic ice reductions, where ice extent can decrease dramatically over periods of the order of a decade. Such abrupt changes can be expected to have a profound effect upon the Arctic freshwater budget, and the outflows from the Arctic to the North Atlantic. We will examine the impact of these dramatic ice retreat events upon the circulation and water mass characteristics of the western North Atlantic.

3.3 Downscaling

Downscaling includes a wide array of methods used to obtain fine-scale information from relatively coarse-resolution (on the order of 100-300 km) global climate models. There are two main approaches to downscaling. In one, a high-resolution physics-based model, such as the regional ocean modeling system (ROMS), is embedded within a GCM in the area of interest. In the other, statistical relationships between large (GCM) scale variables and observed small-scale features are determined and then output from the GCM is used in the statistical model(s) to estimate the regional climate characteristics. While both approaches have strengths and weaknesses, advantages of statistical methods are that they are computational inexpensive, can easily be run using different GCMs and/or scenarios, provide information at specific locations where regional models are limited by their grid scale, can predict variables not included within the regional models and they can incorporate corrections for errors in the mean state and the distribution of variability (e.g. variance) so as to simulate the present day climate reasonably well. The drawbacks of statistical downscaling may include a lack of a cause and effect understanding of the findings and that the relationships may be non-stationary, i.e. statistical values derived from the recent past may not hold in future climates.

A wide variety of statistical downscaling models have been used for climate applications over land (e.g. Blenckner and Chen 2003; Salathé 2005; Chapter 11 of IPCC, 2007) but have been employed much less frequently in the marine environment where there are few long data records needed to establish reliable statistical relationships. However, statistical downscaling may provide useful information for studying the oceans. For example, Overland et al. (2002) investigated how local air-sea interactions known to be important to the ecosystem of the Bering Sea shelf relate to large-scale modes of climate variability, while Heyen et al. (1996) related sea level anomalies along the Baltic Sea coast to large-scale SLP anomalies over the North Atlantic. Given GLOBEC's goal of linking large-scale climate variability and change to regional conditions, we propose to develop statistical models that use output from the IPCC AR4 archive to simulate key biological and chemical as well as physical variables in marine ecosystems. We will use two approaches to downscaling:

1) Develop statistical models using the available long-term data records in the GLOBEC regions. Most current IPCC-class models have reasonable representations of large-scale patterns of climate variability such as ENSO the PDO, NAO, SAM, although with some differences with observations (as evaluated in Chapter 8 of the IPCC report, 2007). Thus statistical relationships between the temporal variability in the large-scale climate patterns in the GCMs and the observed local values can be estimated and then time series (principle components) of these patterns from the IPCC simulations can be used in the statistical models to downscale future changes. For example, since much of the variance of physical and biological quantities along the west coast of North America are related to the first two EOFs of North Pacific SST (Mantua et al. 1997; Bond et al. 2003, Di Lorenzo 2007), regressions based on the corresponding time series in the IPCC simulations - can be used to estimate future changes in the California Current System (CCS) and Gulf of Alaska. In the NEP, the statistical models can be trained using data from CalCOFI, coastal sites such as the Scripps Peer, the Newport line, Line P, GAK, etc.. Similarly, relationships between the Atlantic patterns of variability or fluctuations in the dominant currents can be linked to changes over Georges Bank. Statistical downscaling may prove more difficult over the Southern Ocean due to paucity of data.

2) Develop statistical models based on a ROMS hindcast of the Northeast Pacific Ocean, with a horizontal resolution of 10 km and 30 vertical levels forced with observed atmospheric variables for the years 1958-present (Curchitser et al., 2005, Huang et al., 2007, Hermann et al, 2007). While ROMS can be nested within GCMS to simulate the regional ocean response to global warming, there are still several reasons to use it (as if it were data) to develop statistical models. ROMS is computationally expensive and requires substantial human resources to either drive it with GCM output or nest it within a GCM. While the hindcast will clearly depart from nature, it is able to reproduce many of the observed features associated with large-scale climate variability. For example,

> Curchitser et al. (2005) showed that a hindcast simulation of the North Pacific was able to represent the 1997-98 ENSO event, and the SST anomalies associated with the post 1976 regime shift. In addition, using longer complete records provided by the ROMS hindcast will allow us to test a variety of downscaling techniques for different environments and using a number of GCMS and/or forcing scenarios. Finally, experience in developing statistical downscaling models from ROMS may guide future applications when high-resolution datasets (e.g. ocean color) and/or output from high resolution assimilation systems are of sufficient length to establish reliable statistical relationships.

A number of methods have been employed in statistical downscaling including linear regression or pattern based variants such as canonical correlation analyses (CCA, Karl et al. 1990), analogues, where a forecast is matched to past conditions (Hamill et al., 2006), local rescaling of a predicted variable (Widmann et al. 2003) general additive models (GAMS; Hastie and Tibshirani, 1990) and neural networks (Cavazos, 1997). Hewitson and Crane (1996), Wilby et al. (2004), Haylock et al. (2006) have evaluated the strengths and weaknesses of various downscaling methods, and Wilby et al. (2004) discuss which ones are appropriate for a given application. We will first employ relatively simple statistical approaches, such as regressions, which perform well for monthly and seasonal averages and where the reason behind the relationship is often clear. One can test the efficacy of the predictors, which can include both atmospheric and oceanic variables obtained from the GCMs, and the predictands which can include SST, upwelling, NO_3, plankton biomass, and key GLOBEC species, e.g., cod and salmon stock (note the hindcast only includes physical variables). The statistical relationships will be tested using a jackknife approach (where some of the data is reserved for validation and not included when developing the model). These models will then be used to predict changes due to anthropogenic forcing. Statistical models will then be developed using fields from the ROMS hindcast; since the ROMS fields are both spatially and temporally complete we will explore using additional methods where spatial variability is important, including regional rescaling and GAMS.

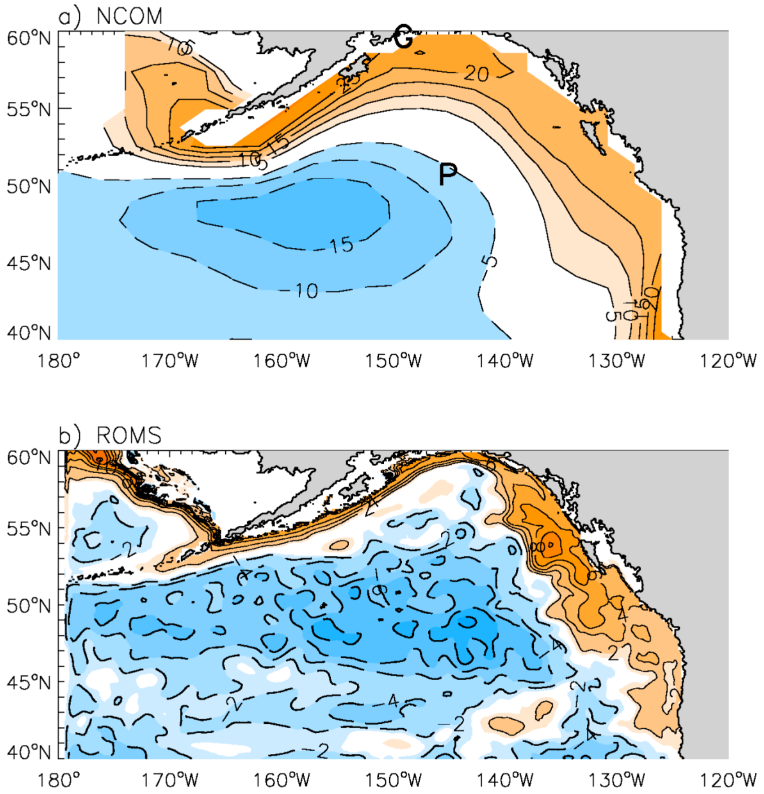

Figure 1. Pycnocline depth difference in the Gulf of Alaska region between a period after the 1976-77 climate regime shift, and a period before the shift, as simulated by a) the NCAR ocean model (NCOM, horizontal resolution ~2°) forced with observed surface fields over the period 1958-1997, and b) the Regional Ocean Modelling System (ROMS, horizontal resolution 13.5-19km). Blue shading is for negative values (shallower pycnocline), while orange shading is for positive values (deeper pycnocline). ROMS is eddy-permitting, while NCOM does not explicitly simulate ocean mesoscale variability. NCOM is representative of the ocean component of climate models. 'P' and 'G' in a) indicate the position of stations Papa and GAK1, respectively, where long-term subsurface observations are available. While the isopycnal depth difference in ROMS is characterized by smaller-scale features and sharper gradients, both models agree in producing pycnocline depths deeper along the coast and shallower in the center of the Gulf after the climate shift. (From Capotondi et al. 2008, in prep.)

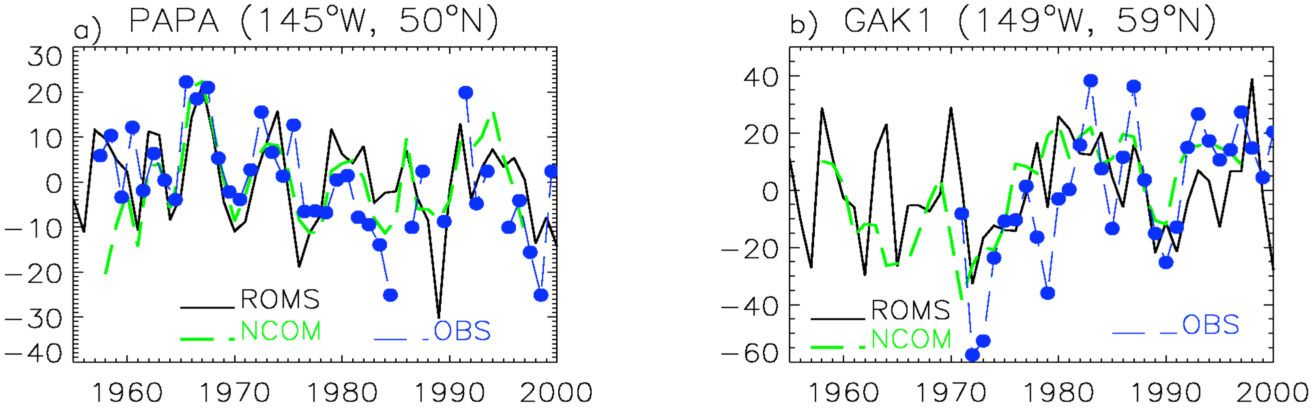

Figure 2. Comparison of winter (Dec.-Apr.) time series of pycnocline depth at a) PAPA, and b) GAK1. The position of the two stations is indicated in Figure 1 by 'P' and 'G', respectively. It can be seen from Figure 1 that PAPA lies in the region of shoaling pycnocline depth, while GAK1 is closer to the coast where the pycnocline deepens. Blue dots connected by a dashed line are observational estimates, usually average of a few measurements/month, green dashed line is the time evolution from the NCOM simulation, and the solid line is from ROMS. Notice that measurements at GAK1 started in 1970. The time series from the models are based on monthly averages of model output, and tend to be smoother than observations. Time series from both models, and in particular that from NCOM, compare relatively well with observations. In particular a decreasing depth trend is seen at PAPA, and an increasing trend is seen at GAK1. (From Capotondi et al. 2008, in prep.)

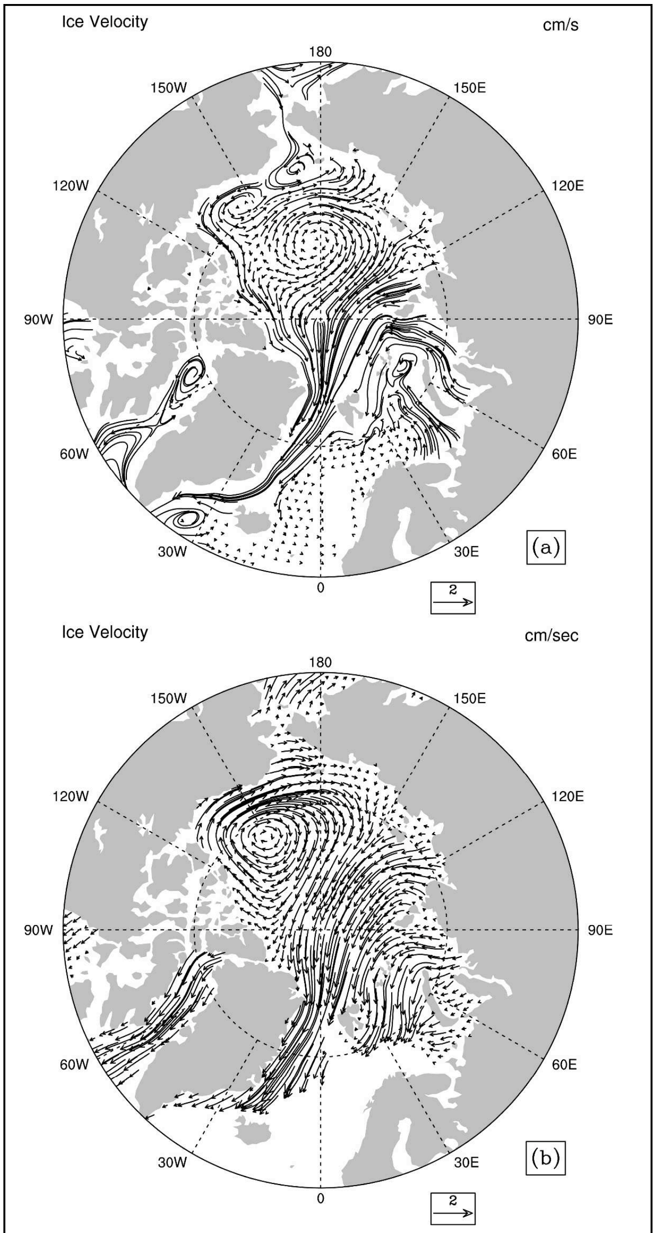

Figure 3. Comparison between the 1980-99 average ice velocities for a) the NCAR-CCSM3 ensemble mean, and b) satellite observations (Fowler 2003). The picture is reproduced from Holland et al. (2006a). Ice motion through both Fram Strait and the Canadian Archipelago is evident. Both Arctic outflows affect the Labrador Sea and Labrador Current.

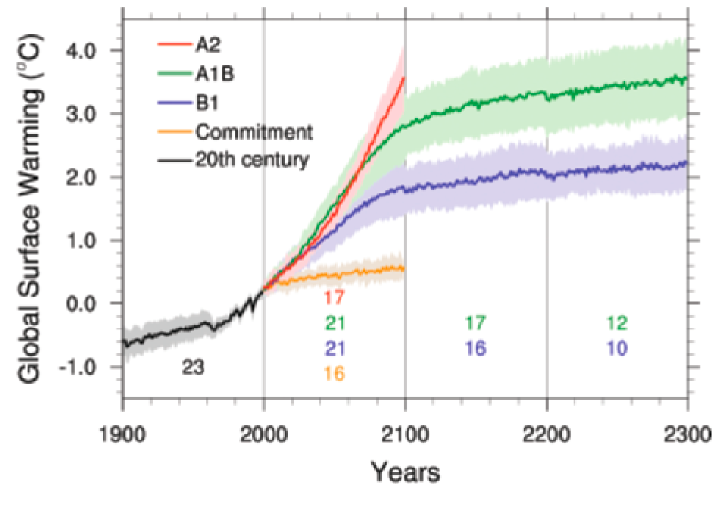

Figure 4. Multi-model average of the IPCC-AR4 surface warming for different scenario simulations. Values past 2100 are for the commitment simulations of the A1B (medium forcing) and B1 (low forcing) scenarios. Lines indicate the multi-model mean, while the shading shows the ± standard deviation intermodel range. The numbers in each period indicates the number of models used for computing the multi-model means. (From Meehl et al. 2007).