Climate-based Forecasts of the Gulf of Maine Ecosystem

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Understanding the mechanisms driving variability in marine ecosystems, especially wild fluctuations in fish abundance and recruitment, has been a major goal of coastal oceanographers since the late 19th Century (Cushing, 1996). From the very beginning, researchers have noted that fluctuations in fish populations are often associated with dramatic regime shifts in marine ecosystems. The most famous of these associations is the "Russell Cycle," a regime shift in the English Channel's plankton community, which occurred in the late 1920's and reversed in the late 1960's (Cushing and Dickson, 1976; Cushing, 1982). The signal of the Russell Cycle was present across trophic levels, including nutrient concentrations, phytoplankton, zooplankton, and fish. A key commonality between the Russell Cycle and other fluctuations in North Atlantic fisheries is their link to basin-scale changes in North Atlantic climate (Dickson et al, 1988; Cushing, 1996; Conover et al, 1995). More recently, the identification of the North Atlantic Oscillation (NAO), a characteristic mode of variability in atmospheric pressure over the North Atlantic, has provided a quantitative measure of North Atlantic climate that has been correlated to changes in marine populations across the Atlantic, including the North Sea (Reid and Planque, 1999; Heath et al., 1999), Baltic Sea (Hanninen et al., 2000), and Gulf of Maine (Conversi et al., 2001; MERCINA, 2001, Pershing, 2001). These results have all depended on long-term monitoring programs, most notably, the Continuous Plankton Recorder (CPR) surveys conducted by the Sir Alistair Hardy Foundation for Ocean Science (SAHFOS) and NOAA Fisheries. However, the results to date have used only a small fraction of the data available from these surveys, with most focusing on a single zooplankton species, *Calanus finmarchicus*. We propose to conduct a synthesis of data from NOAA Fisheries' Marine Resources Monitoring, Assessment and Prediction (MARMAP) Program along with available hydrographic and meteorologic data to develop simple models to forecast the state of the Gulf of Maine ecosystem from climate measurements. These forecasts will be developed to assist NMFS in its mandated efforts to manage living marine resources, including both commercially important and endangered populations.

1 Climate Influences on the Gulf of Maine Ecosystem

We have spent the last several years investigating the impact of climate variations on the physical and biological conditions in the Gulf of Maine and synthesizing results from US and

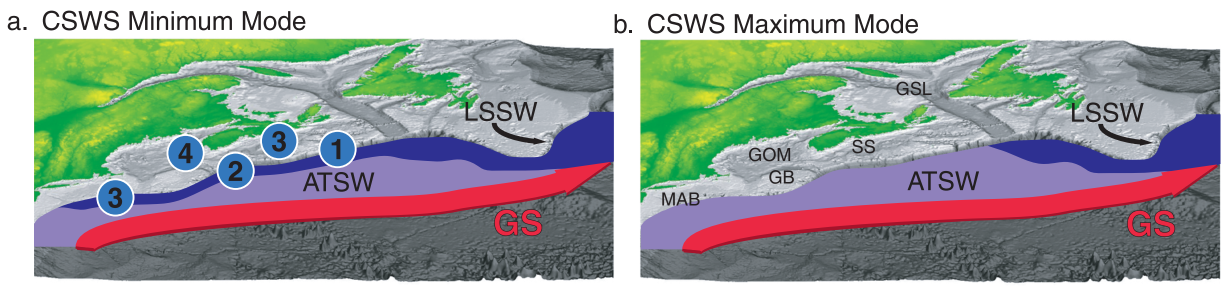

Figure 1: The distribution of Labrador Subarctic Slope Water (LSSW), Atlantic Temperate Slope Water (ATSW), and the position of the Gulf Stream (GS) during the minimum (a) and maximum (b) modes of the CSWS. The numbers in (a) show the first observations of LSSW following the 1996 drop in the NAO: ①= September 1997, ②= January 1998, ③ = February 1998, ④= August 1998 (Drinkwater et al, 2001). Several geographic locations are marked in (b): GSL=Gulf of St. Lawrence, SS=Scotian Shelf, GOM=Gulf of Maine, *GB*=Georges Bank, and *MAB*=Mid-Atlantic Bight.

Canadian studies. This work has allowed us to develop a simple forecast model to predict the hydrographic conditions in the Gulf of Maine from a common measure of regional climate, the NAO Index. We are also able to predict the number of right whale calves based on the abundance of *Calanus finmarchicus*, a key prey species. From these projects, we have learned two important lessons: 1) the response of the physical conditions in the Gulf of Maine to the NAO occurs with a lag, and can thus be predicted, and 2) nonlinear models may be necessary to correctly represent and forecast the dynamics in this system.

1.1 Physical changes in the NW Atlantic: the Coupled Slope Water System

The Gulf of Maine/Western Scotian Shelf region lies within a shifting oceanographic transition zone. This region is located between cold subpolar waters influenced by fluctuations in the Labrador Current and warm temperate waters influenced by fluctuations in the Gulf Stream (Loder et al, 2000). The transitions that occur within this zone are not only physical, as reflected in hydrographic changes, but also biological, as reflected in the changes in composition and relative abundance of plankton. The shifting nature of this transition zone makes the Gulf of Maine region especially susceptible to climate-driven changes in North Atlantic circulation patterns (MERCINA, 2001).

Pickart et al., (1999) first coined the term “Coupled Slope Water System” to describe the system of currents and water masses between the NW Atlantic Shelf and the Gulf Stream. Their analysis of hydrographic sections across this region suggests that the distribution and signature of water masses and the position and strength of currents in this region do not vary independently, but oscillate in a coupled manner. The system has two characteristic “states” or “modes,” each with a unique configuration of water masses and currents. The minimum mode corresponds to a system state in which southwestward transport in the shallow, baroclinic component of the Labrador Current around the Tail of the Grand Banks is intensified, while the hydrographic signature of Labrador Sea Water in the Deep Western Boundary Current is reduced. Enhanced volume transport in the shallow Labrador Current causes a cooler, fresher water mass known as Labrador Subarctic Slope Water (LSSW) to move further down the continental margin, displacing the warmer, saltier Atlantic Temperate Slope Water (ATSW) further offshore (Fig. 1a)[1]. The maximum mode of the CSWS corresponds to a state in which hydrographic signature of Labrador Sea Water in the Deep Western Boundary Current is enhanced, while southwestward transports of the shallow Labrador Current and LSSW are reduced. The reduced volume transports of the shallow Labrador Current and LSSW during this maximum mode result in the frontal boundary of this water mass retreating upstream along the continental margin, allowing ATSW to move towards the shelf (Fig. 1b).

1.1.1 Regional Oceanographic Responses to Modal Shifts in the CSWS

Recently, we have shown that modal shifts in the CSWS are often associated with changes in the North Atlantic climate (Greene and Pershing, 2002; MERCINA, 2001; Pershing, 2001). Analogous to the distribution of water masses and currents in the CSWS, the atmospheric conditions over the North Atlantic fluctuate in a coupled manner, and this characteristic pattern, the NAO, is the dominant mode of atmospheric variability over the North Atlantic (Hurrell, 1995) . The NAO oscillates between two characteristic states, measured by the NAO Index. Positive values of the NAO Index indicate enhanced pressure differences between the Azores' High and Icelandic Low, while negative values indicate reduced pressure contrasts. The changes in atmospheric pressure are associated with changes in the basin-scale wind field and the distribution of temperature and heat (Hurrel, 1995). Although the NAO pattern is present throughout the year, it is strongest in winter (Hurrel, 1995).

From the early to mid-1990's, the NAO Index was in a strongly positive phase, and the CSWS was in its maximum modal state. During the winter of 1996, the NAO Index exhibited its largest single-year drop of the twentieth century, attaining a negative value not seen since the 1960's. This dramatic drop in the NAO Index was followed by a modal shift in the CSWS, with the shallow Labrador Current intensifying and LSSW steadily advancing along the shelf break as far as the Middle Atlantic Bight (Fig. 1a) (Drinkwater et al., 2002).

In addition to its southwestward advance along the shelf break, LSSW also made extensive incursions into the deep basins of the Gulf of Maine and Scotian Shelf (Fig. 2). Although located on the continental shelf, these deep basins contain large quantities of slope water derived from off the shelf (Brown and Irish,1993; Petrie and Drinkwater, 1993; Drinkwater et al, 2001). From the 1970's until 1997, the deep waters of these basins were relatively warm and salty, reflecting their ATSW origin. By the early winter of 1998, LSSW had replaced the deep waters of Emerald Basin on the Western Scotian Shelf and began entering the Gulf of Maine through Northeast Channel (Drinkwater et al, 2001). The relatively cool, fresh LSSW continued to advance through the deeper regions of the Gulf of Maine, replacing the deep waters of Georges Basin by the spring of 1998. By the early autumn of 1998, the hydrographic properties of the deep waters in Jordan and Wilkinson Basins reflected the advective replacement and mixing that had taken place between the invading LSSW and the warmer, saltier ATSW.

[1]LSSW and ATSW were originally named Labrador Slope Water and Warm Slope Water by Gatien (1976). Greene and Pershing (2001) renamed these water masses to indicate their origins.

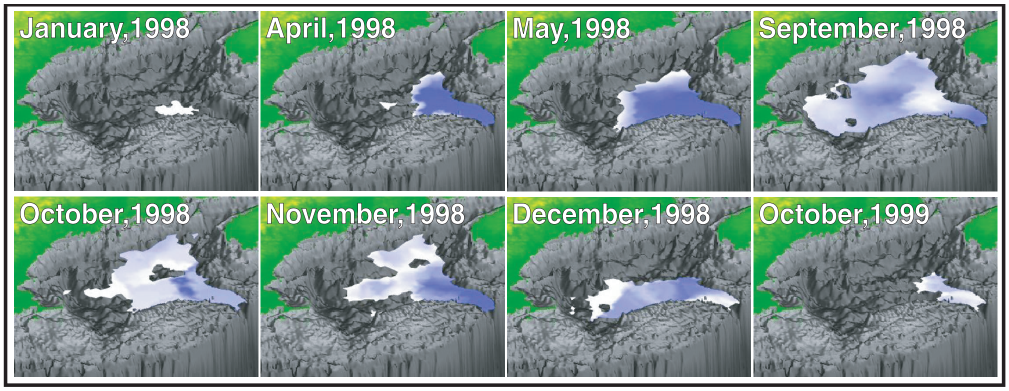

Figure 2: The intrusion and subsequent replacement of LSSW in the deep basins of the Gulf of Maine from January 1998 through October 1999. Percent composition of LSSW in deep waters are indicated in shades of gray, with white corresponding to 20% LSSW and the darkest shade corresponding to 100% LSSW.

The observed hydrographic changes in the Gulf of Maine region were short-lived, however. The large drop in the NAO Index during the winter of 1996 was a single-year event, and the Index returned to positive values for the remainder of the 1990's. Likewise, the CSWS shifted back to its maximum modal state, with the Labrador Current weakening and the frontal boundary of the LSSW retreating northeastward along the Scotian Shelf (Drinkwater et al., 2002). As the supply of LSSW to the region decreased, ATSW returned to its previous position adjacent to the shelf break and began supplying this warmer, saltier slope water to Emerald Basin. By the spring of 1999, the deep waters of Emerald Basin were once again relatively warm and salty. Similarly, the hydrographic signatures of LSSW in the deep basin waters of the Gulf of Maine were steadily lost through advective replacement and mixing, principally with ATSW entering through Northeast Channel. By the end of 1999, the hydrographic conditions in the Gulf of Maine deep basins resembled those prior to the modal shift in the CSWS triggered by the 1996 drop in the NAO Index.

The oceanographic events observed in the Northwest Atlantic during the latter part of the 1990's provide circumstantial evidence that the NAO can alter hydrographic conditions in the shelf ecosystems of the Gulf of Maine region and that these effects are mediated by modal shifts in the CSWS. To generalize from these observations, we now place them in the context of physical time-series data collected from the NW Atlantic over the past half century (Fig. 3).

Based on temperature measurements collected between 150 and 250m, the mean depth of ATSW and LSSW, we constructed a measure of the state of the CSWS called the Regional Slope Water Temperature (RSWT) Index (Fig. 3b). The RSWT Index is the first component from a principle component analysis of the yearly mean temperature in 8 regions in the Gulf of Maine, Scotian Shelf, and adjacent slope waters between 150-200m. This component explains 65% of the variance in slope water temperature data from this region (MERCINA, 2001, Pershing, 2001). Comparing the RSWT Index over the last 50-years with the NAO Index, we conclude that it is reasonable to associate positive (negative) phases of the NAO with maximum (minimum) modes of the CSWS. The decade-long negative phase of the NAO observed during the 1960's coincided with the only extended period in the record

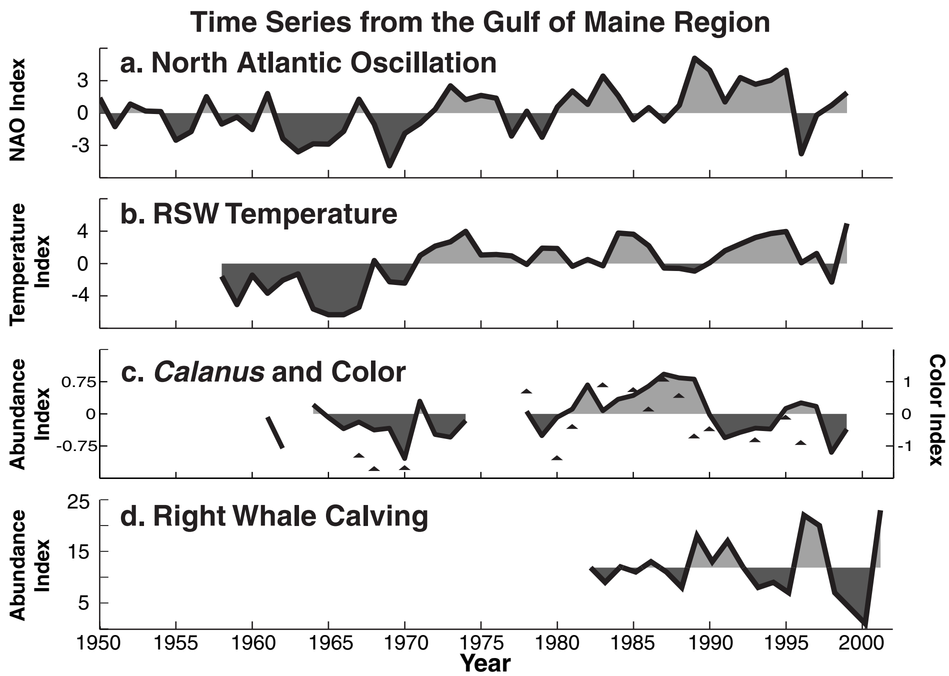

Figure 3: Physical and biological time series from the Gulf of Maine: a. The winter NAO time series, b. The RSWT Index, c. *Calanus* abundance index (line) and the color index (triangles), and d. right whale calving rate. The shading underneath the curves indicates whether the anomalies are positive (light) or negative (dark).

during which the CSWS existed in its minimum modal state. When the NAO changed to a predominantly positive phase for the subsequent three decades, the CSWS also shifted to a predominantly maximum modal state. Furthermore, the RSWT Index has a significant, positive cross-correlation with the NAO at a lag of 1 year[2] ($r=0.56$, $p<0.01$, $n=42$) (Pershing, 2001; MERCINA, 2001). Although the state of the CSWS is associated with the NAO, it is important to remember that the NAO Index is a simple measure of a complicated phenomenon and its predictive value may change through time (Solow, 2002). There are many remaining questions regarding the nature of the NAO and the meaning of the NAO Index, especially in light of the NAO's recent, unusual behavior (Ulbrich and Christoph, 2001). An important aim of our project is to identify specific atmospheric processes that influence the state of the CSWS. We will then use measurements of these processes rather than relying on the NAO Index to act as their proxy.

1.1.2 Population Responses to Modal Shifts in the CSWS

Calanus finmarchicus (hereafter, *Calanus*) dominates the spring zooplankton biomass in the Gulf of Maine and on Georges Bank (Davis, 1987; Durbin et al, 1995; Meise and O'Reilly, 1996), and its early life stages are an important food resource for larval cod and haddock

[2]Filtered time series were used to identify the significant time lags in the cross-correlations of both the NAO vs. RSWT Index and RSWT Index vs. *Calanus* index. The filtering proceedure pre-whitened the series by removing the lag 1 autocorrelation–the only significant autocorrelation in the series.

on Georges Bank (Kane, 1984). The Continuous Plankton Recorder (CPR) surveys in the Gulf of Maine conducted by the NOAA Fisheries have revealed considerable year-to-year fluctuations in the abundance of this species (Jossi and Goulet, 1993; Conversi et al., 2001; Greene and Pershing, 2001). Recently, we completed an analysis of the CPR observations of *Calanus* through 1999 and have started exploring connections between fluctuations in the *Calanus* population and changes in the CSWS. To compare year-to-year changes in *Calanus* with the state of the CSWS, we developed the *Calanus* Abundance Index. The *Calanus* Abundance Index is created by first fitting a seasonal cycle to the log-transformed data (log *Calanus* abundance as a function of julian day). The expected value based on the seasonal cycle is subtracted from each *Calanus* observation to produce a series of anomalies. The Index value for a particular year is then the mean of the anomalies during that year. Removing the seasonal cycle is necessary to avoid biases due to year-to-year differences in the sampling timing and frequency.

The *Calanus* Abundance Index time series for the Gulf of Maine exhibits considerable variability on interannual and interdecadal scales (Fig. 3c). There is a significant, positive cross-correlation between the *Calanus* Abundance Index and the RSWT Index at a lag of three years ($r=0.5$, $p<0.01$, $n=34$; Fig. 4b) and the correlations at lags of 2-4 years are also high (Pershing, 2001; MERCINA, 2001). This time scale agrees with the correlation between *Calanus* and sea-surface temperature (SST) in the Gulf of Maine found by Conversi et al. (2001) and Licandro et al. (2002). Due to strong winter mixing, SST in the Gulf of Maine is strongly related to temperatures below 100m (Petrie and Drinkwater, 1993), implying a relationship between *Calanus*'s correlations with SST and the CSWS. Using the RSWT Index as a proxy for the modal state of the CSWS, we interpret the *Calanus* Abundance Index time series as follows. During the decade of the 1960's, when the CSWS was in its minimum modal state, slope water temperatures and *Calanus* abundance were relatively low. During the 1980's, when the CSWS was predominantly in its maximum modal state, slope water temperatures and *Calanus* abundance were relatively high. During each of the maximum to minimum modal shifts in the CSWS after 1980, *Calanus* abundance declined in subsequent years. Among the recent changes visible in the *Calanus* Abundance Index, the sharp drop of nearly an order of magnitude between 1997 and 1998 stands out as a unique feature. This "*Calanus* crash" occurred after the CSWS system shifted to the minimum mode following the negative NAO winter in 1996 (Greene and Pershing, 2002). As the CSWS returned to the positive mode, *Calanus* abundance increased. The timing between CSWS shifts and changes in *Calanus* concentrations is variable, and determining the exact temporal association between *Calanus* and the CSWS, and the mechanisms linking the two, is a main goal of our proposed research.

The interannual (1997 vs. 1998) and interdecadal (1960's vs. 1980's) changes in the *Calanus* Abundance Index are associated with changes on lower and higher trophic levels. The CPR color index is a qualitative measure of phytoplankton abundance based on the discoloration of the sampling gauze. We produced a time series of spring color index values using the same techniques applied to the *Calanus* data. This time series exhibits many of the same features as the *Calanus* index, including low values in the 1960s and high values in the 1980s (Fig. 3c). The phytoplankton changes suggested by the color index data are possibly a reflection of the different nutrient concentrations that characterize the two slope water types, high concentrations of nitrate and silica in ATSW, low values in LSSW (Petrie and Yeats, 2000). Our project will examine phytoplankton variability more closely by analyzing chlorophyll measurements from the bongo surveys and the abundance of large phytoplankton sampled by the CPR.

Many of the fluctuations in the *Calanus* Index were followed by changes in right whale calving rates (Fig. 3d) (Greene et al., 2002; Pershing and Greene, 2002). From 1982 to 1992, calving rates exhibited no multi-year declines and were relatively stable with a mean rate of 12.4 ± 0.9 (SE) calves per year. These findings are consistent with the relatively high abundance of *Calanus* observed during the 1980's (Fig. 3c). From 1993 to 2001, calving rates exhibited two major, multi-year declines, while the mean rate dropped and became much more variable (11.2 ± 2.7 (SE) calves per year). These findings are consistent with the precipitous drops in *Calanus* abundance observed during the early and late 1990's.

1.2 Current Predictive Capabilities

Our analysis of time-series data from the NW Atlantic suggests a chain of interactions linking the Gulf of Maine ecosystem to North Atlantic climate. The chain begins with basin-wide atmospheric variability associated with the NAO-pattern. The NAO Index reflects winter atmospheric conditions in the Labrador Sea (Dickson et al, 1996). The weather over the Labrador Sea then influences the state of the CSWS by regulating the volume transport of LSSW in the Labrador Current. The physical conditions associated with the CSWS transmit climate signals to populations in the Gulf of Maine. Time lags of a year or more between changes in one component and a responses in another characterize this chain. From a management perspective, these time lags are *the* key feature, as they raise the potential for predictions of ecosystem conditions a year or more into the future. We have already developed systems for forecasting the state of the CSWS from the NAO and for predicting the number of right whale calves from *Calanus* abundance (Greene et al., 2002; Pershing and Greene, 2002).

1.2.1 Forecasting the Coupled Slope Water System

The one- to two-year time lag inherent to the response of the CSWS to NAO forcing offers the potential for oceanographic forecasting on a comparable time scale. We have used the NAO Index and RSWT Index time-series to develop a model for predicting the modal state of the CSWS (Figure 4). The model predicts next year's RSWT Index using values of the RSWT and NAO Indices from the current year:

$$\mathrm{RSWT}^{t+1} = 0.51\mathrm{RSWT}^{t} + 0.46\mathrm{NAO}^{t} - 0.04$$

In our interpretation of the model, the value of the previous year's RSWT Index captures the CSWS's inertia and resistance to change, while the value of the previous year's NAO Index provides the forcing to shift the system from one modal state to another. Using values of the NAO Index and RSWT Index from the previous year, we can predict the RSWT Index for a given year with considerable skill ($R^2 = 0.55$, Figure 4a). Moving from a hindcasting mode to a forecasting mode, a modified version of the model can be used to forecast future probability distributions of the RSWT Index (Figure 4b).

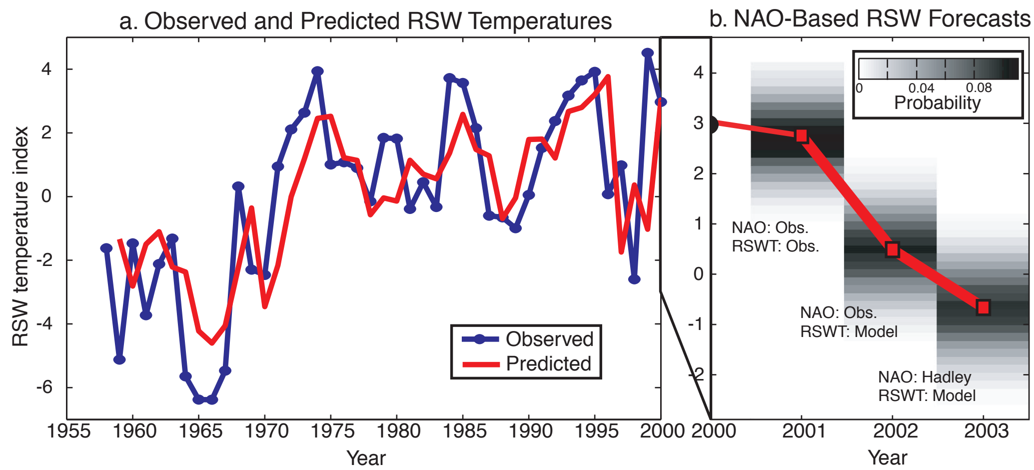

Figure 4: Observed and predicted time series of the RSWT Index. a. Observed RSWT Index time series for 1958-2000 is indicated in black; predicted RSWT Index time series for 1959 -2001 is indicated in gray. b. Forecasted RSWT Index values. Computing the RSWT value requires an observation or estimate of the NAO and RSWT Indices from the previous year. $RSWT^{2001}$ was forecasted with observed values. $RSWT^{2001}$ was then used with the observed NAO Index for 2001 to forecast $RSWT^{2002}$. The forecast for $RSWT^{2003}$ uses the modeled RSWT Index value from 2002 and assumes a negative NAO Index value equal to NAO^{2001}. Probability distributions for the predicted values are shown in shades of gray. The probability distribution for $RSWT^{2001}$ was estimated directly from the model; the probability distributions for $RSWT^{2002}$ and $RSWT^{2003}$ were estimated by a Monte Carlo procedure, which carried over error terms from earlier predictions into those of later predictions.

1.2.2 Forecasting Right Whale Reproduction

With fewer than 400 animals, the North Atlantic right whale is one of the most endangered marine species. Today, the small, remnant population of right whales in the western North Atlantic relies almost exclusively on feeding grounds in the Gulf of Maine/Western Scotian Shelf (GOM/WSS) region (Winn et al. 1986). The whales move between the main feeding grounds in a pattern that is closely tied to the likelihood of finding large concentrations of copepods, especially *Pseudocalanus* spp. and *Calanus* (Woodley and Gaskin, 1996; Mayo and Marx, 1989; Wishner et al., 1995). Thus, the *Calanus* population in the Gulf of Maine is the main food resource for North Atlantic right whales. Furthermore, variability in *Calanus* abundance is likely an important source of variability in right whale reproduction.

To investigate the connection between right whale calving and *Calanus* we built a simple model of right whale reproductive biology (Greene et al., 2002; Pershing and Greene, 2002). Analysis of the right whale photographic catalog maintained by the New England Aquarium suggests that right whales require at minimum three years between births (Knowlton et al., 1994). After a pregnancy of roughly a year, each mother gives birth to a single calf in the calving region off of the southeast US. The mother-calf pairs then migrate to the Gulf of Maine, arriving in Cape Cod Bay in late winter. After the calves are weaned, the mothers require at least one year of recovery before they can support another pregnancy. Our model captures this cycle by partitioning female whales among three states: recovering, pregnant,

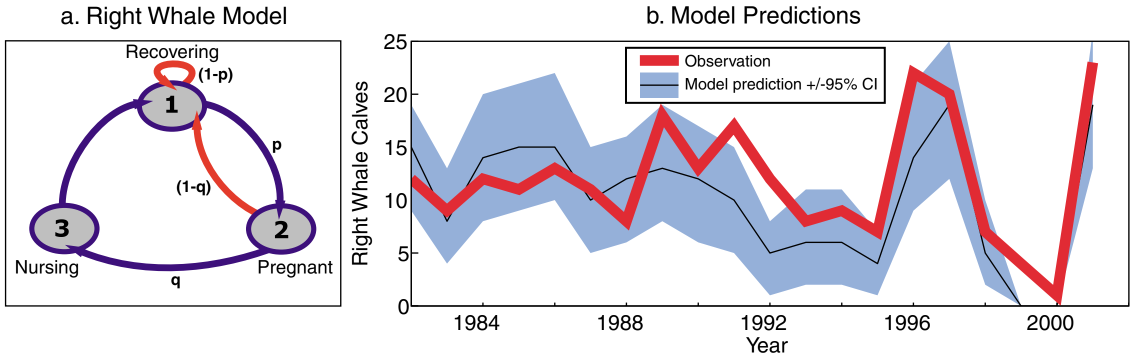

Figure 5: Predictions of yearly number of right whale calves based on the abundance of *Calanus* in the western Gulf of Maine. a. The model assigns females to one of three states: recovering, pregnant, and nursing. *Calanus* abundance determines the probability (**p** and **q**) that the females successfully transition to the next state (black arrows). If a whale fails, she is placed in the recovery state (gray arrows). The two parameters controlling **p** and **q** were found using a genetic algorithm (see text). b. Predictions from the model using parameters from the genetic algorithm. The number of calves observed is shown as a thick gray line. The best-fit model was run 1000 times, and the expected number of calves is shown in blue and outlined by 95% confidence intervals. *Calanus* abundance in 1999 was not included during model fitting, so the predictions for 2000 represent an "out of sample" test of the model. The predictions for 2001 assume a mean level of *Calanus* in 2000.

or nursing (Figure 5a). The whales advance to the next state with a probability determined by food abundance (functions **p** and **q** in Figure 5a). If a whale does not advance, then she is moved to the recovery phase. The probability of advancing is related to normalized food concentration, C. For values of C below τ, the saturating food concentration, the probability of advancing increases linearly, from 0 to $p_{\max}$. If C is above the saturating value, the probability is constant. We created several input time series from the CPR *Calanus* data representing bimonthly periods in four regions: Cape Cod Bay, Western Gulf of Maine, Eastern Gulf of Maine, and the Scotian Shelf.

For each of the food input series, we used a genetic algorithm (Michalewicz, 1996) to find the four parameters ($p_{\max}$ and τ for the transitions from recovery to pregnancy and pregnancy to nursing) that produced the best fit between the predicted and observed numbers of right whale calves. For this investigation, our null hypothesis was that all input series with autocorrelation structure similar to the *Calanus* series will produce equally good predictions. To test this hypothesis, we compared the predictions using the *Calanus* data to predictions from 500 random time series with autocorrelation structure similar to the *Calanus* series. This analysis identified *Calanus* abundance in the Western Gulf of Maine during late-spring and early-summer as a good predictor of right whale reproduction (goodness-of-fit > 95% of the values from the random analysis). The region and season identified by this analysis likely corresponds to the Great South Channel, an important right whale feeding area during the late spring (Wishner et al., 1995). The accuracy of our predictions improves if we average the Western Gulf of Maine data over the entire year. The expected number of calves in each year does a good job predicting the overall patterns in the observations (Figure 5, thin black line). The predictions and observations are strongly correlated ($R^2 = 0.65$, $p < 0.01$), and most of the observations fall within the 95% confidence interval surrounding the predictions (Figure 5, light-gray region). *Calanus* data from 1999 were deliberately excluded from the parameter fitting; thus, the prediction for 2000 represents an out of sample test of our model. The predictions for 2001 were made assuming average *Calanus* concentrations. With this assumption, the model slightly underestimates the number of calves in 2001. If the relationship between *Calanus* and the RSWT Index holds in this year, it is likely that *Calanus* will be relatively abundant in 2000, potentially improving the accuracy of our right whale predictions.

2 Project Goals

As outlined in the "Request For Proposals," a central goal of the Coastal Ocean Program is to provide decision makers with "high quality scientific information and predictive tools in formats appropriate to promoting near-term improvements in coastal ecosystem management." There are two key components to this mission. The first is to develop the scientific understanding of the ecosystem in question, and the second is to synthesize the scientific knowledge into a format that can be readily incorporated into the decision-making process. Our project will address both components to develop a series of predictive models for the Gulf of Maine ecosystem.

The Gulf of Maine contains several important commercial fisheries, most notably those for cod and haddock on Georges Bank and in the Gulf. Assessing the recruitment of these species is a key part of NOAA Fisheries research in this region. Accurate estimates of recruitment are vital to determining the abundance of these species and for setting catch limits. The ability to forecast recruitment a year or two in advance would allow fisheries managers to develop long-range plans for these populations. Our research goals are directed towards developing the knowledge and tools necessary for these predictions and focus on understanding the influence of basin-scale climate variability on the Gulf of Maine ecosystem. Although variability in local atmospheric forcing (heat and fresh water flux) is certainly an important source of variability in the conditions in the Gulf of Maine, forecasts of these conditions are not available with enough lead time to be incorporated into the management process. In contrast, the forcing associated with the NAO influences the Gulf of Maine after a year; and thus, supports the 1-2 year forecasts we seek. We have outlined four specific objectives for our research:

Goal 1: *Characterize the changes in the physical environment of the Gulf of Maine associated with basin-scale climate variability.*

Goal 2: *Refine our understanding of the connection between Calanus and climate.*

Goal 3: *Characterize the response of populations other than Calanus (phytoplankton and zooplankton) to the physical changes.*

Goal 4: *Understand how the physical and biological changes impact fish recruitment.*

We have already made considerable progress on the first goal. We have developed a simple measure of the state of the CSWS and have demonstrated the ability to predict the

CSWS state from the NAO Index. For Goal 1, our project will refine our knowledge of the processes leading to modal shifts in the CSWS, characterize physical conditions in the Gulf of Maine associated with CSWS state beyond deep-basin temperatures, and will determine the relative strength of basin-scale forcing through the CSWS relative to local forcing in the Gulf of Maine.

Calanus' position as the dominant spring zooplankter in the Gulf of Maine, makes understanding the causes of variability in this species an important step in characterizing changes in the Gulf of Maine ecosystem. Several studies have already linked variability in *Calanus* abundance in the Gulf of Maine to the NAO (Conversi et al., 2001) and to the CSWS (MERCINA, 2001; Pershing, 2001). Although large changes in the *Calanus* Abundance Index are typically preceded by changes in the RSWT Index, the time scale at which this occurs is not consistent. Furthermore, the mechanisms linking *Calanus* to the CSWS are not yet known. To address Goal 2, we will take a closer look at the relationship between *Calanus* and physical conditions in the Gulf of Maine. We will also gauge the relative strength of physical forcing and trophic interactions as sources of variability in *Calanus*. An important part of this research will be to move away from yearly averages to more closely examine temporal variability in *Calanus* abundance. This is a necessary step to examine the relationship between *Calanus* and fish recruitment which depends on temporal overlap between the two populations (i.e. the match-mismatch hypothesis, see Cushing, 1990).

To more fully understand the variability in the Gulf of Maine ecosystem, it is necessary to move beyond *Calanus* and examine phytoplankton and other zooplankton taxa. Although early *Calanus* stages are an important component in the diet of larval fish, at least on Georges Bank (Kane, 1984), they are certainly not the only food source. Smaller copepods such as *Pseudocalanus* spp. and *Metridia lucens* are also important prey for larval cod and haddock (Marak, 1960). Examining the interannual variability in these species will allow us to more accurately assess the impact of climate variability on the feeding environment of larval cod and haddock.

Finally, we will examine the association between the recruitment of larval fish and the physical and biological properties developed under the first three goals. The end result will be a model linking fish recruitment to climate state. This model will be similar in spirit to our model that forecasts right whale births from *Calanus* abundance. At present, when the NAO Index value for a given winter is published, we can then forecast the RSWT Index with some quantifiable error. The RSWT Index forecast can then be passed to the model of *Calanus* abundance developed for goal 2, and the *Calanus* prediction can be used to predict whale births 2 or more years in the future. Each subsequent year will bring new information, and we can replace forecasted terms such as the RSWT Index with observed quantities; thereby continually improving the accuracy of the forecast.

An important goal of our project will be to identify the optimal set of measurements to use as inputs into our models. For our purposes, we can rigorously define criteria to select the optimal measurements based on the predictive value of each measurement and its cost in terms of sample collection and processing. This kind of cost-benefit analysis is essential to providing effective forecasts: no matter how effective a forecast system is, if the information it requires is too costly to obtain or takes too long to analyze, the system will be useless. As an example, consider our right whale forecasts. Our analysis of data between 1981 and 1999 identified the *Calanus* abundance in the Western Gulf of Maine as a good predictor of right whale births. However, analyzing CPR samples is costly and time consuming. Our predictive skill using *Calanus* abundances from May-June is nearly as good as that using yearly-averaged data. Although we can't change the data needs of our model or the costs (in both time and money) of analyzing the CPR samples, identifying a critical time-period and area and increasing the priority of these samples would allow us to produce timely right-whale forecasts.

3 Proposed Research

Time-series analysis is a powerful tool for identifying important relationships among variables and identifying potential processes accounting for these relationships. Our original time-series analyses examined only a few taxa (*Calanus* C5-6 and CPR color) and used only standard linear techniques (cross-correlations and principal components analysis). For this project, we will augment standard techniques with new techniques in non-linear time-series analysis (NLTA) to examine the relationships among a wider range of biological and physical series. This project will provide predictive indices that can be used to manage the Gulf of Maine ecosystem.

3.1 Data Sets

The MARMAP Program consists of two complimentary surveys, one using the CPR and another using bongo nets. The MARMAP CPR program began in 1961 and consists of a single transect across the Gulf of Maine, between Boston, MA and Cape Sable, NS. The CPR is towed from a ship-of-opportunity at a depth of ∼10m with approximately one transect occurring each month. The data set consists of spatially indexed abundance of several zooplankton taxa including *Calanus finmarchicus* C5-C6, *Calanus* spp. C1-C4 (mostly *C. finmarchicus*), adult *Pseudocalanus* spp., *Centropages typicus*, *Oithona* spp., and *Metridia lucens*. Several large phytoplankton species are also counted from the CPR samples. The CPR provides a consistent time series with good temporal resolution, and thus, it will form the basis of our new time-series analysis.

We will use data from the MARMAP bongo surveys to augment our CPR analysis. The protocol for the bongo surveys was established in 1977. A survey consists of a series of stations, and at each station, paired bongo nets are used to collect plankton from 200 m (or near the bottom) to the surface. Although the protocol has remained stable, the distribution of the stations and the frequency with which they are sampled has changed over time. Compared to the CPR survey, the bongo surveys provide better spatial extent, but the survey coverage is inconsistent and limited in temporal resolution and extent.

Time series of larval fish recruitment from the Gulf of Maine and Georges Bank are freely available from Dr. Ransom Myer's online database. We will focus our analysis on cod and haddock and will examine other species if time permits.

In addition to plankton abundance, our study requires information on atmospheric and oceanographic conditions in the NW Atlantic. The best source for hydrographic data in this region is from the Bedford Institute of Oceanography's (BIO) climate database. This data base contains hydrographic and other physical measurements from the Gulf of Maine to the Labrador Sea extending back to the early part of this century. The data are freely available over the internet, and we have a good working relationship with several researchers at BIO. Oceanographic data from BIO will be augmented by hydrographic measurements collected concurrently with the bongo and CPR sampling. We will also use meteorological data from NOAA buoys in the Gulf of Maine and from the NCEP/NCAR reanalysis.

3.2 Nonlinear Time-series Analysis

Our previous statistical analysis of the relationship between biological time series in the Gulf of Maine and their physical environment relied on cross-correlation analysis, a simple linear method. The main limitation of cross-correlation analysis is that it can only detect linear relationships. Non-linearity is a well-known feature of the equations of motion (Pond and Pickard, 1983) and many ecological models (May, 1986). Accounting for the nonlinear relationship between *Calanus* and right whales was a key factor in our success in forecasting this species. Furthermore, nonlinear systems forced by a signal at one period can exhibit variability at multiple periods (Pascual and Ellner, 2000). Thus, linear techniques such as cross-correlation analysis could fail to detect potentially interesting and important relationships. For these reasons, we propose to focus our new time-series work on non-linear time series analysis.

Non-linear time series analysis can provide insight into community dynamics and their relationship to physical and climatic forcing. Prime examples are the recent result connecting cholera outbreaks in Bangladesh with ENSO (Pascual et al, 2000) and modeling primary production (Belgrano et al., 2001). As described in Pascual and Ellner (2000), the goal of nonlinear time-series analysis is to find the function f that best reproduces the dynamics of an observed variable N (e.g. *Calanus* abundance). This function is assumed to depend on earlier values of N, values of variables suspected to interact with N (e.g. chlorophyll), and external forcing E (e.g. RSWT Index). Lagged values of N allow the analysis to include the effect of unobserved variables such as the abundance of unknown or unsampled predators or prey (Takens, 1981; Kot et al., 1988). The model f is found using a feed-forward neural network (FNN). For a particular set of variables, the FNN procedure will find the best model; however, as with polynomial regression, complex models (more variables, larger networks) will always give a better fit. Typically, several models of varying complexity are fit to the data, and the model with the best combination of accuracy and simplicity is chosen. The relationship between accuracy and simplicity is specified formally using a Generalized Cross Validation (GCV) criterion:

$$V_c = \left(\frac{RMS}{1 - p\frac{c}{n}}\right)^2$$

where RMS is the root-mean-square residual error between model and observations, p is the number of fitted parameters, n is the sample size, and c is the "penalty term" which is typically set near 2 (Nychka et al., 1992). Setting $c = 2$ biases the results towards simpler models but greatly reduces the chance of selecting a spurious, overly-complex model (Pascual and Ellner, 2000).

The NLTA conducted by Pascual and Ellner (2000) focused on nonparametric approaches (i.e. nothing was assumed about the structure of f except the variables involved). Our analysis will use this approach to identify the key variables and their lags by selecting from a range of models using the GCV criterion. The weakness of this approach is that it is difficult to "see inside" a neural network to determine the mechanisms represented by the model, although it is possible to gain some understanding of the model by experimenting with contrived inputs. To improve our mechanistic understanding, we will use current knowledge of the physical and biological processes in the region to build parametric models representing plausible physical and ecological relationships. The same GCV and neural network techniques can be applied to select among the possible parametric models. For both nonparametric and parametric approaches, model diagnostics will be used to closely examine the residuals of the fitted models. Finally, we will apply the techniques developed by Bailey et al. (1996) to construct confidence intervals for predictions from the selected models. These predictions will then be compared with observations after 1999 to provide an out-of-sample test of our models. These years will provide an interesting test, given that the NAO Index for winter 2001 was negative.

To demonstrate the value of this approach, we used the NLTA techniques to explore the relationship between the RSWT Index and yearly average *Calanus* abundance in the Western Gulf of Maine. Neural nets with either one or two hidden layers were fit to *Calanus* abundance using one or more RSWT Index series lagged by one to three years. Although the models with two hidden layers often had much higher R^2 values, in all cases the GCV criterion chose the simpler one-layer models. Among the one-layer models, the model using the RSWT Index from the year before and the model using the RSWT Index from one and two years before had very similar GCV values, and the second model had a correlation coefficient comparable to our original linear correlation (R^2=0.33). The 1-2 year lag identified by the NLTA are more believable than the three year lag indicated by the cross-correlations, and there are several processes that could explain the 1-2 year time scale (see Hypotheses 2b-c below).

3.3 Addressing Hypotheses

Above, we outlined four broad goals for this project. These goals focus on characterizing the physical response of the Gulf of Maine to basin-scale climate forcing and understanding how these physical changes influence populations in the region. For each goal, we postulate a set of hypotheses that we will test by building a series of non-linear and conventional statistical models, although the descriptions below focus on NLTA. Each analysis will identify a set of measurements that can be used to predict important ecological properties such as *Calanus* abundance and larval fish recruitment. Parametric modeling is a key component of our research plan that will allow us to relate the relationships suggested by the statistical models to specific physical and biological mechanisms.

3.3.1 Goal 1: Characterizing physical conditions

Hypothesis 1a: *The modal state of the CSWS is strongly determined by past winter conditions in the Labrador Sea.*

Hypothesis 1b: *The modal state of the CSWS is a good indicator of hydrographic conditions above the slope water layer.*

Hypothesis 1c: *Anomalously warm, mild winters or increased fresh water input will reduce the influence of winter mixing and reduce the correlation between CSWS state and upper water column hydrography.*

The physical conditions in the Gulf of Maine result from a combination of local and remote forcing, each with a characteristic time scale. Hypotheses 1a-c postulate relationships between conditions in the Gulf of Maine and remote and local forcing. Petrie and Drinkwater's (1993) hydrographic analysis suggests that the distribution of slope water masses in the CSWS is controlled largely by the volume transport in the shallow Labrador Current. Recent analysis of TOPEX altimetry by Han and Tang (2001) have linked transport variability in the Labrador Current to the wind-stress curl over the Labrador Sea. These results suggest several properties in the Labrador Sea that may account for the connection between CSWS state and the NAO. By moving from the NAO towards more tangible factors directly influencing the CSWS, we hope to improve our ability to predict the state of the CSWS.

To address hypothesis 1a, we will use NLTA techniques to select a model which best predicts the RSWT Index from physical conditions in the Labrador Sea in winter. These two studies suggest three properties in the Labrador Sea that could influence the state of the CSWS: air temperature, sea ice extent, and wind stress curl. We will repeat this analysis using a new RSWT Index formed from monthly rather than yearly slope water temperatures. The monthly analysis will allow us to examine the seasonal patterns in the CSWS and the timing of modal transitions. Together, the monthly and yearly analyses will provide a clearer picture of the role of remote forcing in determining the state of the CSWS.

Hypothesis 1b comes directly from the work of Petrie and Drinkwater (1993) who found that surface temperatures across the Northwest Atlantic are strongly related to temperatures in the Slope Water layer due to strong winter mixing. Although the water masses indicated by the RSWT Index are relatively deep (150-250m), strong winter mixing allows these water masses to influence surface properties such as temperature and nutrient concentration, but only after winter. Thus, unless the modal shift occurs exactly in winter, we should expect to observe changes in surface properties one year after a change in the RSWT Index..

Any process that stabilizes the water column during winter will tend to decouple surface temperatures from bottom temperatures. Thus, winters with decreased heat loss or reduced wind stress would appear as deviations from the relationship postulated in Hypothesis 1b. Increased freshwater input in the form of river input or relatively fresh Scotian Shelf Water (Smith, 1983) would also act to stabilize the water column. During the 1990's, the proportion of Scotian Shelf Water has increased substantially, reducing overall salinity in the Gulf of Maine (Dr. David Mountain,*pers. comm.*)[3]. We hypothesize that during periods such as the 1990's with decreased surface salinities, the influence of slope-water type on surface properties will be reduced (Hypothesis 1c).

We will begin to address hypotheses 1b-c by first searching for a model to predict SST from temperature in the Slope Water layer. If Hypothesis 1c is correct then adding a combination of surface salinity, wind speed and direction, and heat flux should improve the model. We can compare the relative importance of local surface forcing or salinity changes vs. remote forcing in the form of the CSWS by comparing the predictions from the model using only slope water temperatures and those from a model using only local surface properties. The comparison can be done in a rigorous fashion using polynomial regression. We will also examine of the relationship between Scotian Shelf Water input and basin-scale climate.

3.3.2 Goal 2: Linking *Calanus* and climate

Hypothesis 2a: *Calanus abundance in the Gulf of Maine is positively related to CSWS state at a lag of 1-2 years.*

[3]Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA 02543

Hypothesis 2b: *The correlation in 2a results from changes in the abundance of Calanus in the Slope Water Sea (SWS) or in advection from this region.*

Hypothesis 2c: *Processes local to the Gulf of Maine alter the development of the Calanus population in the Gulf of Maine, but are less important than changes in 2b.*

Although our earlier analysis found a correlation between *Calanus* and the RSWT Index, several issues still remain. First, we need to understand the temporal relationship between changes in the CSWS and *Calanus*. Second, we need to identify the processes producing the correlation. Due to *Calanus*'s prominence in the diet of commercial and threatened species in the Gulf of Maine, understanding the mechanisms driving interannual variability in *Calanus* will increase our chance of forecasting the status of commercial and threatened populations.

Hypotheses 2a comes directly from our previous analysis, and the initial step of our proposed *Calanus* work will be to reassess the temporal relationship between *Calanus* and CSWS state. As described in section 3.2 we have already begun to apply NLTA techniques to address this question. The NLTA study indicates that *Calanus* abundance in the Western Gulf of Maine is a function of the RSWT Index values from one to two years earlier. As described above, we should expect a one year lag between the RSWT Index and and several surface properties. Thus, the winter after a change in the CSWS, we should see a change in surface properties such as nutrient concentrations and temperature. These surface properties would affect the *Calanus* populations on two time scales. First, changes in growth rates in the Gulf of Maine/Scotian Shelf region would have an immediate effect on *Calanus* abundance in the Gulf of Maine. At the same time, the same surface properties will be manifest throughout the CSWS region, and *Calanus* should respond over the entire region. The Gulf of Maine is only a small part of the CSWS, and much of the CSWS to the north and east lies upstream from the Gulf of Maine. Changes in *Calanus* in these regions would be felt in the Gulf of Maine the following year–two years after the RSWT Index change.

We have already begun applying NLTA techniques to address Hypothesis 2a. The next step in this analysis is to compare the monthly RSWT Index that will be developed to address Hypotheses 1a-c with monthly *Calanus* abundance. Examining the relationships at a higher temporal resolution will allow us to characterize changes in the timing of *Calanus* abundance. These temporal changes may be especially important when considering the relationship between *Calanus* and larval fish recruitment.

As discussed above, changes in *Calanus* abundance in adjacent regions could be an important source of variability for the Gulf of Maine population. The influence of advection on shelf populations of *Calanus* is magnified by this species' requirement for deep water during diapause. A consequence of this overwintering strategy is that *Calanus* populations on continental shelves, must be re-established each spring by animals transported from deeper water. The deep basins in the Gulf of Maine and on the Scotian Shelf harbor some overwintering *Calanus* (Sameoto and Herman, 1990; Durbin et al, 2000); however, strong flow through the region implies that the Gulf of Maine/Scotian Shelf *Calanus* population is not self-sustaining and requires regular transport of individuals from populations located off the continental shelf (Miller et al, 1998). The SWS, the region between the shelf break and the Gulf Stream harbors one of the three self-sustaining *Calanus* populations (Bucklin et al, 2000), and this is likely the ultimate source of *Calanus* for the Gulf of Maine and Western Scotian Shelf (Head et al., 1999). Thus, variability in the abundance of *Calanus* in the SWS, or changes in the coupling between this region and the shelf region, would lead to variability in *Calanus* abundance in the Gulf of Maine (Hypothesis 2b). In the SWS, the nutrient concentration in the mixed layer should be strongly influenced by the distribution of nutrient rich ATSW relative to nutrient poor LSSW (Petrie and Yeats, 2001). During the minimum mode of the CSWS, LSSW penetrates further into the SWS (Figure 1), and we might expect reduced phytoplankton production and fewer *Calanus* in these years.

If our hypotheses are correct, then the state of the CSWS would determine the abundance in the SWS and the degree of cross-shelf transport. These factors would determine the baseline abundance of *Calanus* in the Gulf of Maine. Variations in conditions in the Gulf of Maine would cause the abundance to deviate from the baseline (Hypothesis 2c). These conditions include temperature and food availability–the two key factors controlling copepod reproductive and development rates, as well as predator abundance.

Hypotheses 2b and 2c contrast the influence of local processes–temperature and phytoplankton variability in the Gulf of Maine–and advective inputs. Ideally, one would address these hypotheses by hindcasting circulation fields for a range of years, and then using a data assimilation approach to infer the abundance of *Calanus* upstream or the population growth rates (e.g. McGillicuddy et al., 1998). Unfortunately, we believe that this approach will take more than the two years allocated for COP Synthesis and Forecasting; however, we are presently developing a proposal, to be submitted elsewhere, that will take this approach. For the present project, we propose to develop a novel parametric model using the NLTA tools to address Hypotheses 2b-c. The approach is similar conceptually to the data assimilation approach advocated above; however, it is specifically tailored to take advantage of the long temporal record of the CPR data.

The rate of change in plankton abundance in a parcel of water is determined by local growth and advective inputs. This rate can be formally stated as an advection-reaction equation, which for *Calanus*, takes the form:

$$\frac{\partial C}{\partial t} = r(T, P) * C - m(C, t) + u \cdot \nabla C + \epsilon \tag{1}$$

where C is *Calanus* concentration, r incorporates reproduction and development as a function of temperature T and phytoplankton P (measured as chlorophyll), m is the mortality rate, and u is the horizontal velocity. This function assumes that local growth is related to *Calanus* in a linear fashion. Several studies have measured the development and egg production rates for *Calanus* in the Northwest Atlantic across a range of temperatures and phytoplankton abundances, measured as chlorophyll concentration (Plourde and Runge, 1993; Runge and Plourde, 1996; Campbell et al., 2002), and we will use these empirical relationships to define r. The mortality (m) and advection ($u \cdot \nabla C$) terms are unknown, and our task is to use the CPR information to determine their seasonal and interannual variability. We will first construct annual cycles for temperature and chlorophyll in the CPR region using data collected during the bongo surveys (e.g. O'Reilly and Zetlin, 1998). From this information, we can determine the average annual cycles of mortality and advective input required to minimize the error between the observed annual *Calanus* cycle and that predicted by equation 1. To find these cycles, we will use the NLTA techniques to find a mortality function dependent upon C and time and an advection function depending only on time. We will then use the NLTA techniques to develop a conversion function to compute chlorophyll from CPR color index values and phytoplankton abundance. This conversion function will be used to determine the value of r over the entire CPR survey period. Using these values and the annual mortality and advective input functions, we can model *Calanus* over the CPR period.

The final step is to determine the factors producing deviations between modeled and observed C. If Hypotheses 2b-c are correct, then these deviations can be explained by a function of only the RSWT Index. To evaluate these hypotheses, we will use the NLTA techniques to compare the ability of functions using the RSWT Index, earlier *Calanus* abundance (since mortality is a function of C), predator abundance from the bongo surveys, or combinations of these inputs to model the deviations. For hypothesis 2c to be correct, then adding this function should increase the accuracy of the predictions to a greater degree than adding interannual changes in r.

3.3.3 Goal 3: Population changes beyond *Calanus*

Hypothesis 2a: *Phytoplankton standing stocks are positively associated with the state of the CSWS.*

Hypothesis 2b: *Variability in copepods other than Calanus is more closely related to local conditions.*

To date, only a few studies have used the Gulf of Maine CPR data to examine species other than *Calanus*; however, the CPR database contains information on many zooplankton taxa and several large phytoplankton species. We plan to conduct NLTA-based studies on both phytoplankton and other copepods. ATSW has higher concentrations of both nitrate and silica than LSSW. Based on these differences and our initial analysis of the CPR color index, we hypothesize that phytoplankton abundance should be positively related to the RSWT Index, and should follow RSWT Index by one year due to winter mixing. To test this hypothesis, we will use NLTA techniques to build a model predicting phytoplankton abundance using the RSWT Index. Assuming that the RSWT Index is a good proxy for nutrient concentrations, we can begin to examine the importance of variability in nutrient input relative to variability in stratification in the development of the spring phytoplankton bloom. Incorporating surface processes identified during the test of Hypothesis 1c should enhance the predictive skill of the phytoplankton NLTA. Comparing the GCV criteria of combinations of forcing will allow us to determine the relative importance of stratification versus nutrient variability.

Previous studies have noted marked interannual variability in non-*Calanus* copepods in the Gulf of Maine (Jossi and Goulet, 1993; Licandro et al., 2002). For the purpose of predicting ecosystem status in the Gulf of Maine, we need to establish to what degree the variability in these populations is related to basin-scale climate. The other copepods in the Gulf of Maine, most notably *Centropages typicus*, *Metridia lucens*, *Oithona* spp., and *Pseudocalanus* spp., tend to be smaller and reproduce more quickly than *Calanus*. Unlike *Calanus*, the life histories of these species do not require deep water. For these reasons, we expect the other copepods in the Gulf of Maine to be less sensitive to advective changes or conditions in the SWS, instead, we expect that local environmental conditions are a more important source of variability. Although surface temperature, phytoplankton abundance, and other local properties may provide a link to the CSWS (e.g. Hypotheses 1b and 3a), we expect that the variability in other copepods should be less tied to the CSWS than is *Calanus*. Prior studies by Jossi and Goulet (1993) and Licandro et al. (2002) support this hypothesis. Jossi and Goulet's principal components analysis found that the variability patterns in all copepods except *Calanus* were related, and the study by Licandro et al. (2002) found that the cross correlations functions between SST and *Metridia lucens* and *Oithona* were similar and that these functions were inversely related to that between *Calanus* and SST. To address Hypotheses 3b-c, we will take the same parametric modeling approach described above for *Calanus.*

3.3.4 Goal 4: Climate variability and larval fish

Hypothesis 4a: *Copepod abundance (not merely Calanus) is a good predictor of larval fish recruitment.*

Hypothesis 4b: *Including indicators of local physical conditions will significantly improve predictions of fish recruitment.*

Hypothesis 4c: *Climate-based predictions of biological and physical properties will allow multi-year forecasts of fish recruitment.*

Larval fish recruitment can be influenced by many factors, including the abundance of food and physical processes that advect larvae away from productive regions. Hypothesis 4a recognizes that larval fish are opportunistic feeders and the association between any single prey and recruitment may be low if other prey become more abundant. To address this hypothesis, we will build NLTA models using each copepod taxa, singly and in combination, as input. Comparing the GCV values should allow us to identify a set of species that allow us to predict the recruitment of each fish species. However, trophic processes are not the only factors influencing fish recruitment. Temperature can directly influence growth and feeding rates and has been identified as an important mechanism linking cod recruitment in the Barents Sea to climate (Ottersen and Stenseth, 2001). Strong wind events (Lewis et al., 1994; Lewis et al., 2001) and Gulf Stream rings (Ryan et al., 2001) could advect larvae away from productive regions. Our analysis will attempt to identify a set of physical measures that is a good predictor of fish recruitment, especially for cod and haddock stocks on Georges Bank and in the Gulf of Maine. We will focus on local temperature, wind speed and direction, and the RSWT Index. We will produce an NLTA model for each input series and fish species, and then we will examine combinations of inputs. To gauge the relative importance of trophic vs. physical factors, we will build a multiple regression model combining the predictions from the best trophic model and the best physical model. The coefficients from the regression will give an estimate of the relative importance of these processes. Our analysis will attempt to distinguish between these factors (trophic vs. physical) and to identify a set of physical and biological measures that are good predictors of larval fish recruitment.

3.4 Interfacing with Management

The ultimate goal of our research project is to develop a model that can predict the recruitment of commercial fish species in the Gulf of Maine region. By focusing on physical and biological properties with strong links to climate, we increase our chances of developing a system of models that can forecast recruitment 1-2 years in the future. Furthermore, our work should lead to a better understanding of the long term variability of the Gulf of Maine ecosystem, especially its response to basin-scale climate variability. This understanding has implications for a range of management issues. Our goal is to provide a framework to address specific management objectives: assessment of fish and right whale stocks, and to make our work and those of related projects accessible to a range of managers, allowing them a chance to direct research towards management needs.

Part of the mission of NOAA's Northeast Fisheries Science Center is to provide accurate assessments of the current status of commercially exploited fishes and protected species and to project the potential consequences of future management actions. Projections are particularly important when rebuilding plans must be enacted for depleted fish stocks, as in most New England fisheries. In this project, age-structured assessments of Georges Bank cod and haddock will be used to evaluate the use of the predictive climate models for improving models of stock-recruitment dynamics for these primary groundfish stocks. Stock-recruitment models are routinely needed to provide age-structured projections of the future stock size and landings to fisheries managers (Brodziak et al. 2001). These projections have been used to quantify the effects of potential management measures and form the basis for rebuilding plans that have been developed for depleted New England groundfish stocks (Brodziak et al. 1998). Obviously, quantifying the effects of changes in oceanographic conditions on deviations from fitted stock-recruitment models could improve the accuracy of such projections. This, in turn, would provide better information to managers who need to make difficult choices among restrictive measures to rebuild these highly productive groundfish stocks. In a similar manner, the predictive climate models may be useful for evaluating strategies to reduce mortality on protected right whale calves in years of high calving success. We will work with Dr. Richard Merrick to begin incorporating our right whale results into management of this population (see attached letter).

Although our specific goal is to develop models that can enhance predictions of fish stocks, our study will generate a wealth of information on the response of the Gulf of Maine ecosystem to basin-scale climate. This information will be relevant to management issues beyond fish stocks and right whales. Our work may have bearing on other commercial species or important processes such as harmful algal blooms. In order to provide a way to distribute our findings to a wide range of interested parties, we plan to hold two yearly workshops. The purpose of these workshops will be to bring together researchers and managers who are interested in fisheries management issues in the Gulf of Maine. The workshops will allow the research community to share their knowledge with managers and will provide a forum for managers to help focus research towards specific management issues. The meetings will be held in southern New England to maximize participation from the NOAA Fisheries Labs in Rhode Island and Massachusetts. We have requested funds to host these meetings and to provide travel expenses for 10 participants outside our group. This will allow us to bring in researchers and managers from states and provinces surrounding the Gulf of Maine, beyond the core personnel identified in this proposal.

3.5 Project management

For this project, we have assembled a team of researchers with expertise in biological oceanography, computational oceanography, and statistics. J. Jossi will serve as data manager, supervising the acquisition of NMFS biological data, especially data from the MARMAP CPR and bongo surveys. B. Bailey will oversee the time-series analysis that will be conducted by A. Pershing and C. Greene. J. Brodziak and L. O'Brien will work closely with Pershing to develop the time-series models for larval fish recruitment and to integrate them with stock recruitment models. In addition to the workshops, we have requested travel funds to allow face-to-face collaboration. We plan for Bailey, Brodziak, and O'Brien to visit Cornell, and for Pershing to travel to Illinois, Woods Hole, and Narragansett.

4 Conclusion

Developing a predictive understanding of shelf ecosystem responses to climate change will be one of the most difficult challenges confronting oceanography in the twenty-first century. The means for achieving such a predictive understanding must include retrospective studies of long time-series data to establish relationships among ecologically important variables. Such an integrated approach forms the basis for the research outlined in the present proposal. Through a careful investigation of the response of the Gulf of Maine ecosystem to basin-scale climate forcing, our study will develop a series of models to provide 1-2 year forecasts of important physical and biological processes. These forecasts will enhance the ability of NOAA Fisheries to manage commerically important and threatened species in the Gulf of Maine.

Milestone Chart

	Goal 1	Goal 2	Goal 3	Goal 4
Fall	Build monthly RSWT Index, evaluate Labrador Sea forcing			
Winter		Compare *Calanus* to monthly RSWT Index		Compare recruitment to monthly RSWT Index, local physics
Spring	Finish comparing surface forcing to CSWS			
Summer		parametric *Calanus* modeling		
Fall			Compare phytoplankton to surface T and S and RSWT Index	Compare recruitment to *Calanus*
Winter			parametric modeling of other copepods	Compare recruitment to other copepods
Spring			Combine physical and trophic model	
Summer				Merge forecast model with stock assessment

The chart above outlines our research milestones. This arrangement spreads the fish recruitment work throughout the project to allow maximum feedback between management and research. We have deliberately allocated more time for the initial NLTAs, especially the physical oceanography and *Calanus* work. This will allow us to gain experience with the NLTA techniques, and we anticipate that less difficulty applying these techniques to phytoplankton, other copepods, and fish recruitment. We plan to hold our first workshop meeting in autumn, 2002 to allow management input at the initial stage and to provide an opportunity for our team to plan our activities. The second workshop will be held in spring, 2004.

Budget Justification: Cornell University

This project will be directed by two Principal Investigators, Dr. Andrew Pershing and Dr. Charles Greene. Dr. Pershing will have overall responsibility for the project and will direct the time-series analysis. Dr. Greene will assist with the analysis and will coordinate the workshops. In terms of salary costs, we are requesting 4.0 month of funding per year to support Dr. Pershing and 2.0 months of funding per year to support Dr. Greene.

In terms of travel costs, we are requesting funds to support travel to attend the workshops planned for this project and for travel to one national meeting. We are also requesting travel funds to allow Dr. Pershing to travel once to Illinois to work with Dr. Bailey and southern New England to coordinate work with Drs. O'Brien, Brodziak, and Jossi. We are requesting $6,000 per year (10 people at $600) to offset the travel expenses of workshop participants. We are also requesting $3,000 for a laptop computer that will allow us to analyze and display data at these workshops, and two PC workstations ($3,000 each) for data analysis. The remaining expenses are necessary to cover miscellaneous costs associated with this project.

Budget Justification: University of Illinois Urbana-Champaign

We are requesting 1 month of summer salary per year for Dr. Barbara Bailey who will work with Dr. Pershing on the time-series analysis. She has help develop many of the nonlinear analysis techniques we will apply and is an invaluable asset to the project.

In terms of travel costs, we are requesting funds for Dr. Bailey to travel to attend the workshops planned for this project, for one trip to Ithaca, NY to work directly with the Cornell group, for travel to one national meeting. The remaining expenses are necessary to cover miscellaneous costs associated with this project.

Budget Justification: NOAA Northeast Fisheries Science Center

We are requesting 1 month salary per year for both Dr. Loretta O'Brien and Dr. Jon Brodziak. Drs. O'Brien and Brodziak oversee the stock assessments for cod and haddock in the Gulf of Maine, and their participation is critical to ensure that the forecast models can be applied to management goals. Salary support for 10% of Mr. Jack Jossi's time will be devoted to this proposed project through his full time appointment with U.S. Dept. of Commerce-NOAA.

We are requesting travel funds to allow Drs. O'Brien and Brodziak to visit Cornell, and the remaining expenses will be used to cover miscellaneous expenses associated with this project.

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