THE RESPONSE OF THE NORTHWEST ATLANTIC'S COUPLED SLOPE WATER SYSTEM TO THE NORTH ATLANTIC OSCILLATION: THE BEGINNING OF A NEW REGIME?

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ABSTRACT

The northwest Atlantic's slope waters respond as a coupled system to North Atlantic Oscillation-mediated differences in upstream forcing from the Labrador Current. Hydrographic responses of this Coupled Slope Water System (CSWS) typically result in warmer (colder) and saltier (fresher) slope waters during positive (negative) phases of the NAO. A regional slope water temperature (RSWT) index was developed to characterize these changes in slope-water hydrography (MERCINA, 2001).

Since the 1970s, the NAO and RSWT indices have been predominantly positive, with occasional NAO phase reversals preceding drops in the RSWT index. Here, an empirical model developed for predicting the RSWT index's response to NAO forcing is explored to determine its recent performance and whether any improvements can be made. The model has performed well for the past decade, and no major improvements appear justified.

In 2009, the NAO entered a multi-year period of negative index values, something that has not been observed since the 1960s. We predict that the RSWT index will respond strongly to this negative NAO forcing, resulting in a modal shift in the CSWS similar to that observed in 1998. Changes in remote forcing from the Arctic are hypothesized to be behind the recent changes in NAO behavior.

BIOGRAPHICAL SKETCH

Matthew Donal Connelly received his Bachelors degree in Science of Earth Systems with a concentration in Ocean Sciences at Cornell University in May 2009. He began working on his degree of Master of Science at Cornell University in the fall of 2009. During that time he analyzed data from an intertidal transect study at Shoals Marine Lab on Appledore Island in Maine, as well as hydrographic and climate data in the northwest Atlantic Ocean. He assisted in teaching Introduction to Oceanography, Satellite Remote Sensing in Biological Oceanography, and Conservation Oceanography in Hawaii.

This thesis is dedicated to the faculty at Cornell University who supported my education in extraordinary ways.

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LIST OF ABBREVIATIONS

ATSW	Atlantic Temperate Slope Water
CSWS	Coupled Slope Water System
LSSW	Labrador Subarctic Slope Water
NAO	North Atlantic Oscillation
RSWT	Regional Slope Water Temperature

INTRODUCTION

The North Atlantic Oscillation (NAO) is the major basin-scale mode of inter-annual to inter-decadal climate variability in the North Atlantic (Hurrell *et al*., 2003; Hurrell and Deser, 2010). As quantified by the NAO index, this climate mode is characterized by shifts in the winter atmospheric pressure gradient over the North Atlantic Basin. Positive values of the NAO index correspond to an enhanced pressure gradient between the two major atmospheric pressure centers in the North Atlantic, the Azores subtropical high and Icelandic subpolar low. Negative values correspond to a reduced pressure gradient between these two atmospheric centers of action.

The NAO index has been significantly positive for much of the past four decades. Many observations and models have attributed this extended positive phase to increased concentrations of greenhouse gases and/or reduced concentrations of stratospheric ozone in the atmosphere (Hurrell *et al*., 2006; Hurrell and Deser, 2010). During the past forty years, there have been only a handful of observed NAO index values that were significantly negative, and none of these values were sustained for more than one winter. However, negative values have been observed for the past three winters (2009, 2010, 2011), with 2010 exhibiting the lowest value observed since 1969, just before the NAO settled into its current, long-term positive phase. Based on events associated with the last major drop in the NAO index in 1996, we anticipate that this recent phase reversal will lead to a major reorganization of ocean circulation patterns in the northwest Atlantic.

The upper slope waters of the northwest Atlantic (shallower than 800 m) have been shown to respond as a coupled system to basin-scale changes in climate (Keigwin and Pickart, 1999; Pickart *et al*., 1999; MERCINA, 2001). During positive NAO conditions over the past forty years, the coupled slope water system has existed mostly in its maximum modal state, with warm, salty Atlantic Temperate Slope Water (ATSW) positioned along the continental shelf break until it converges with Labrador Subarctic Slope Water (LSSW) at a front near the Gulf of St. Lawrence (MERCINA, 2001). This maximum modal state typically coincides with reduced transport in the shallow, baroclinic component of the Labrador Current around the tail of the Grand Banks and an enhanced hydrographic signature of Labrador Sea Water in the Deep Western Boundary Current (Pickart *et al*., 1999).

In 1996, the largest, single-year drop of the NAO index during the 20th century occurred. This event had major repercussions for the physical oceanography of the northwest Atlantic (MERCINA, 2001). Within two years of the large drop in the NAO index, the CSWS shifted from its maximum to its minimum modal state. The southwestward transport of the Labrador Current around the tail of the Grand Banks intensified and relatively cold and fresh LSSW advanced along the shelf break, displacing the ATSW offshore and reaching as far southwest as the Middle Atlantic Bight. By August 1998, LSSW had spilled into the deep basins of the Gulf of Maine and Western Scotian Shelf, mixing with the relatively warm and salty resident ATSW-derived deep waters of those basins.

These observed oceanographic changes did not last long, however, as the NAO index's large drop was only a single year event, and it returned to more positive values for the remainder of the 1990s. Consequently, the Labrador Current weakened and the frontal boundary of the LSSW retreated northeastward along the Scotian Shelf. As the supply of LSSW from the Labrador Current diminished, ATSW returned to its position along the shelf break and began supplying bottom waters to the deep basins of the Gulf of Maine and Western Scotian Shelf. By the end of 1999, oceanographic conditions in these deep basins resembled conditions prior to the NAO-associated modal shift in the CSWS (Greene and Pershing, 2003; MERCINA, 2001).

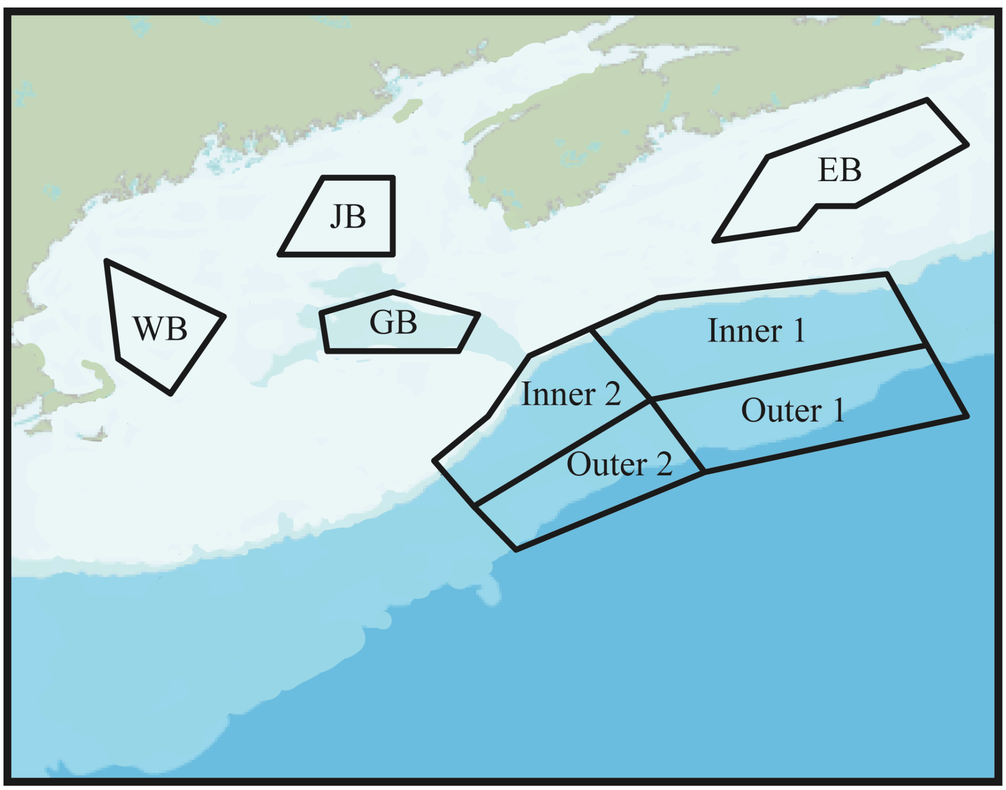

Figure 1. Map of the geographic sectors in the Gulf of Maine/Scotian Shelf region of the northwest Atlantic, as defined in the BIO database. Data from within these sectors were used in the principal components analysis conducted to construct the RSWT index. The sectors are labeled as follows: Wilkinson Basin = WB, Jordan Basin = JB, Georges Basin = GB, Emerald Basin = EB, Inner Slope 1 = Inner 1, Outer Slope 1 = Outer 1, Inner Slope 2 = Inner 2, Outer Slope 2 = Outer 2. Bathymetric map courtesy of Fisheries and Oceans Canada.

To quantify the relationship between the NAO and CSWS, a regional slope water temperature (RSWT) index was developed to serve as a proxy characterizing the state of the CSWS (MERCINA, 2001). The RSWT index is the dominant mode derived from a principal components analysis (PCA) of eight slope-water temperature anomaly time series from different sectors in the Gulf of Maine/Western Scotian Shelf region (Figure 1). The regional hydrographic data used in the PCA are from the Bedford Institute of Oceanography (BIO) hydrographic database (http://www2.mar.dfo-mpo.gc.ca/science/ocean/database/data_query.html).

Comparing the time series of the NAO index and RSWT index shows that the CSWS commonly responds a year or two after phase reversals in the NAO (Figure 2a,b) (MERCINA, 2001). When the NAO was in a negative phase during the 1960s, the CSWS operated exclusively in its minimum modal state, with relatively cold and fresh conditions along the shelf break. From the early 1970s to the 2000s, the NAO index has been predominantly positive, and the CSWS typically has exhibited the relatively warm and salty conditions characteristic of its maximum modal state. Seven times during the past forty years (1977, 1979, 1985, 1987, 1996, 2001, and 2006), the NAO index has dropped to negative values for a single year. In each case, the CSWS responded to the phase reversal by shifting towards the colder slope water temperatures characteristic of its minimum modal state. Although shifts following the 1977 and 1979 phase reversals were relatively weak, the ones following the NAO phase reversals of 1987, 1989, 1996, and 2006 were stronger and lasted for several years. In each case, the CSWS responded to the phase reversal after a one to two-year time lag, with low values of the RSWT index observed in 1989, 1998, and 2007.

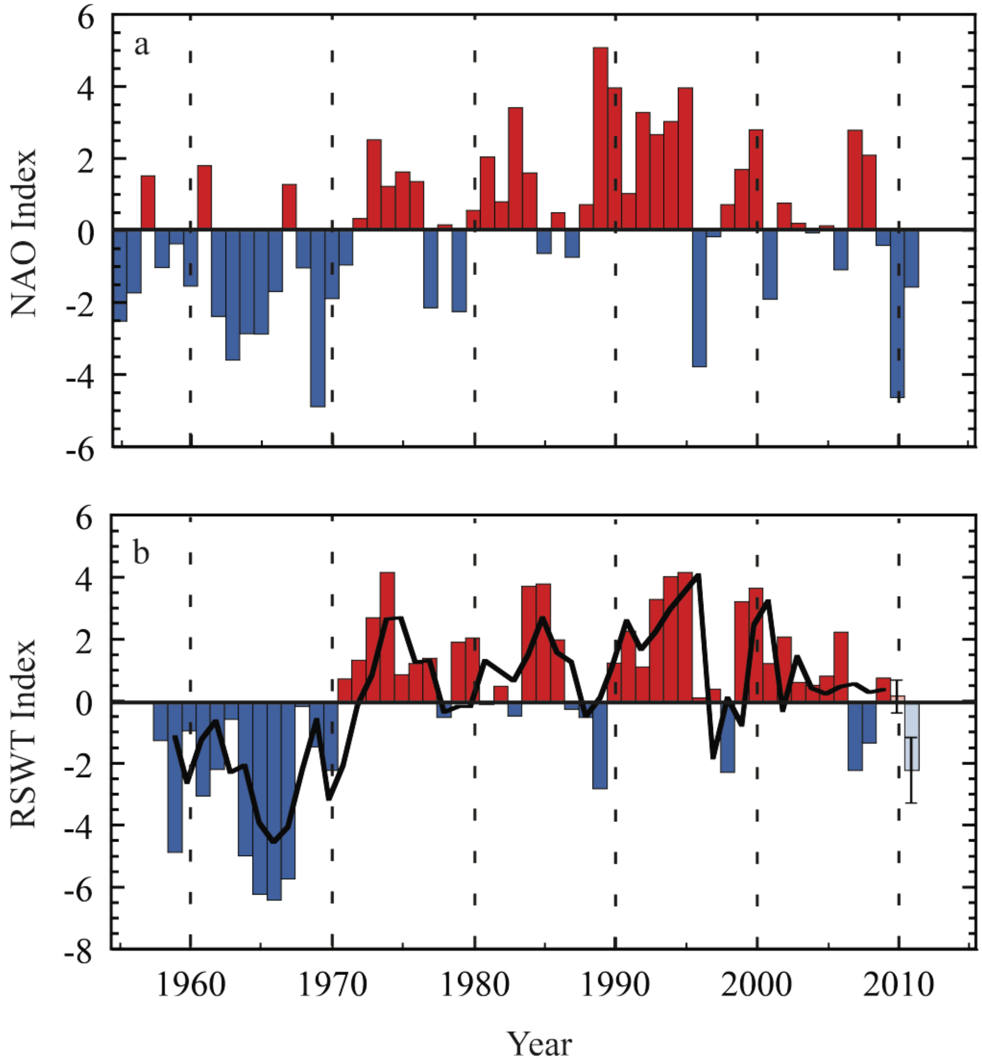

Figure 2. Comparison of time series from the North Atlantic. (a) Annual values of the winter (December-March) NAO index (1955-2011). Values are from station-based measurements taken in Lisbon, Portugal, and Stykkisholmur, Iceland. (b) Annual values of the RSWT index (1958-2009) are shown as dark-colored vertical bars. The solid line represents predicted values for years with measured RSWT index values. Forecasted RSWT index values for 2010-2011 appear as pale-colored vertical bars. Error bars represent a 95% prediction interval.

If these past observations are an indicator of the future, then the effects of the recent NAO phase reversal should appear in the RSWT time series between 2011 and 2012. Since the recent drop in the NAO index is comparable in magnitude but longer in duration than the one observed in 1996, one might expect that the consequences will be similar or greater this time around.

METHODS AND RESULTS

One method of forecasting the effects of the recent drop in the NAO index on the CSWS is through the use of statistical models. The one- to two-year time lag in the response of the CSWS to changes in the NAO allows us to use recent observations to forecast future oceanographic conditions. Greene and Pershing (2003) developed the following simple multiple linear regression model to predict the RSWT index for a given year by using the previous year's values of the station-based winter NAO index and RSWT index:

$$\text{RSWT index}_t = 0.51(\text{RSWT index}_{t-1}) + 0.46(\text{NAO index}_{t-1}) - 0.02 \qquad (1)$$

Now that each time series is extended to include a decade of new data (1958-2009), the current study explores ways of potentially improving the Greene and Pershing (2003) model.

In our first exploration, we retain the multiple linear regression approach of the original study (Greene and Pershing, 2003), but use it to evaluate whether a PCA-based winter NAO index produces stronger cross-correlations with the RSWT index than the station-based winter index used previously. Winter NAO index values based on a PCA of sea-level pressure data can be found along with the more commonly used values based on station differences in sea-level pressure at the National Center for Atmospheric Research website maintained by James Hurrell (http://www.cgd.ucar.edu/cas/jhurrell/indices.html). Both index types perform better with a lag of one year rather than two years. The station-based winter NAO index, regardless of the definition of the winter period (December – February: R^2_{DJF}=0.35, January – March: R^2_{JFM}=0.33, and December – March: R^2_{DJFM}=0.31) performs better than the PCA-based one (all R^2<0.30). Although it does not show the strongest cross-correlation, the December to March winter NAO index is the one we have chosen to continue using. We justify this choice by pointing out that the model results are not significantly different regardless of the winter period chosen and the use of the December – March index facilitates comparisons with previous studies.

In exploring results from the regression analysis more closely, we examined the residuals to determine if they conform to the model's assumptions. The results demonstrate that the assumption of a linear relationship between the NAO index and RSWT index is appropriate. In addition, there is no evidence for an autocorrelation in the residuals (Durbin-Watson test: D=2.2, α=0.05), nor the emergence of any obvious pattern that would suggest a means for improving the model.

Although the model performs better with a lag of one year rather than two, responses of the CSWS to changes in the NAO commonly vary with a lag between one to two years. This suggests that including NAO index values at lags of both one and two years might improve model performance. When the model was run with the additional variable NAO $index_{t-2}$, no significant improvement was found. In addition, using the mean of both variables, NAO $index_{t-1}$ and NAO $index_{t-2}$, only results in a dampening of the year-to-year variability in the predicted time series without significantly improving the model's performance.

Although the results of our explorations thus far indicate that equation (1) is a valid model for forecasting responses of the CSWS to NAO forcing, we propose that an even simpler model can achieve nearly identical results. Our multiple regression analysis using the expanded time series reveals that the intercept term is not significantly different from zero. Therefore, this term can be omitted from the equation without affecting the model's validity. The new, simpler model is fit by equation (2) and has a R^2=0.53 ($P<0.001$).

$$\text{RSWT index}_t = 0.5(\text{RSWT index}_{t-1}) + 0.5(\text{NAO index}_{t-1}) \qquad (2)$$

CONCLUSION

Short-term, Inter-annual Predictability

In practice, equation (2) allows forecasts to be made for a given year as soon as the NAO index and RSWT index values become available for the previous year. While NAO index values are based only on winter data and published by summer of the same year, the RSWT index values are annual and cannot be calculated until the year is complete. This becomes the limiting factor in using the model as a predictive tool and reduces forecasting abilities to at most one year. In the future, it may become possible to estimate the RSWT index from measurements taken during critical periods or specific seasons within the year. Such an approach may extend the lead-time of the model's forecasts by a few months.

The lead-time constraints on the model's forecasting abilities are dissatisfying, especially when major changes appear to be in progress. The most recent slope and deep-basin temperature time-series data available from the BIO database are from 2009. Without any measured values, we can only speculate about responses of the CSWS to NAO forcing in 2010 and 2011. Figure 2b shows a hypothetical value for RSWT $index_{2010}$ based on the observed RSWT index and NAO index values from 2009. According to the model, the hydrographic conditions in 2010 should be similar to those observed in 2009. Around this time, the CSWS was in a neutral state, recovering from a shift towards its minimum modal state following the drop in the NAO index in 2006. This is consistent with the one- to two-year time lag in the CSWS's response to NAO forcing. However, we anticipate that the CSWS will shift towards its minimum modal state by 2011. Figure 2b shows a forecasted value for RSWT $index_{2011}$ based on an observed NAO index value for 2010 and the predicted RSWT index value for 2010. If these predictions prove to be correct, it suggests that the CSWS will respond to an extent observed only three times since the early 1970s. With the strongly negative NAO index values seen in both 2010 and 2011, we predict that the CSWS will exhibit characteristics of its minimum modal state beyond 2012. A prolonged occurrence of minimum modal state conditions could lead to some major changes in northwest Atlantic's ecology in the coming years, impacting all levels of the marine food chain (Drinkwater *et al*., 2003; Pershing *et al*., 2004; Greene *et al*., in prep.).

Long-term, Inter-decadal Predictability

While short-term, inter-annual predictability may be limited, there might be opportunities to develop more predictive skill on longer, inter-decadal time scales. An examination of the NAO index time series reveals that there are some inter-decadal patterns clearly visible. The NAO varies on longer time scales from periods of mostly negative values, such as the decade of the 1960s, to periods of mostly positive values, such as the last three decades of the 20th century. This multi-decadal positive phase was unusually persistent, a pattern attributed by numerous authors to be a response to anthropogenic climate change, both greenhouse warming and stratospheric ozone depletion (Hurrell *et al*., 2006; Hurrell and Deser, 2010). More recent analyses of Arctic climate change, however, suggest that a complex series of atmospherecryosphere-ocean feedback mechanisms may now be counteracting the direct effects of greenhouse warming and pushing the NAO in an opposite direction.

In the Arctic, greenhouse warming has led to historically unprecedented reductions in summer sea ice extent. The loss of summer sea ice exposes more of the Arctic Ocean's darker surface waters to incoming solar radiation. The subsequent absorption of this solar radiation and excess heating of the ocean has two important feedbacks in the climate system. First, a portion of the excess heat goes to further accelerate the summertime melting of sea ice, forming the basis for what has been referred to as the ice-albedo feedback mechanism (Deser *et al*., 2000). Second, much of the remaining excess heat is gradually released to the atmosphere during the autumn, decreasing the meridional temperature gradient between the Arctic and subarctic latitudes (Overland and Wang, 2010). This initial decrease in the meridional temperature gradient leads to a weakening of the atmosphere's Polar Vortex. A weakened Polar Vortex is less able to constrain colder Arctic air masses to latitudes above the Arctic Circle, and its breakdowns during the winter allow cold air to spill out of the Arctic and into lower latitudes. Such Arctic outbreak events further diminish the meridional temperature gradient, favoring a tendency towards more negative NAO conditions (Arctic Report Card: http://www.arctic.noaa.gov/reportcard/). The strongly negative winter NAO conditions of 2010 and 2011 are consistent with these ideas and suggest that a return to an extended regime of negative NAO conditions is now more likely.

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