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The flip-side of the North Atlantic Oscillation and modal shifts in slope-water circulation patterns

Abstract—A large single-year reversal in the phase of the North Atlantic Oscillation (NAO) during 1996 led to a dramatic shift in the slope-water circulation patterns of the northwest (NW) Atlantic. Analyses of time-series data collected from the region over the past half century show that both physical and biological responses are commonly elicited by such phase reversals in the NAO. Here, we use a model developed from time-series data to predict responses of the NW Atlantic slope-water circulation patterns to phase reversals in the NAO.

The Atlantic and Pacific Oceans experienced extreme events in ocean climate during the late 1990s. Although overshadowed by the global impacts of the most intense El Nino–Southern Oscillation event on record (Chavez et al. 1999; McPhaden 1999), a large single-year drop in the North Atlantic Oscillation (NAO) index (Hurrell 1995) during 1996 had major regional- and basin-scale impacts for several years throughout the North Atlantic Ocean (Kushnir 1999; Hurrell and Dickson in press). One of the most dramatic consequences of this event was a modal shift in the slope-water circulation patterns of the northwest (NW) Atlantic (MERCINA 2001). By placing these occurrences in the context of time-series data collected from the region over the past half century, it is possible to show that such modal shifts are commonly associated with phase reversals in the NAO (MERCINA 2001).

For the past quarter century, the NAO index has exhibited an unusually persistent, positive trend (Langenberg 2000; Hurrell et al. 2001), an observation consistent with the rise of oceanic heat content and models of greenhouse warming (Ulbrich and Christoph 1999; Barnett et al. 2001; Hoerling et al. 2001; Levitus et al. 2001). During winter 1996, however, the NAO index exhibited its largest single-year drop of the 20th century, attaining a negative value not seen since the 1960s. This large drop in the NAO index led to a large-scale reorganization of ocean circulation patterns in the NW Atlantic over the subsequent 2 yr (MERCINA 2001). To comprehend the magnitude of these changes, one must first understand conditions prior to the event.

The NW Atlantic's slope waters respond as a coupled system to major changes in climate (Keigwin and Pickart 1999; Pickart et al. 1999). During the positive NAO conditions of the past quarter century, this coupled slope water system (CSWS) has operated predominantly in its maximum modal state, with relatively warm and salty Atlantic Temperate Slope Water (ATSW) positioned along the shelf break until it converges with Labrador Subarctic Slope Water (LSSW) at a front near the Gulf of St. Lawrence (Fig. 1a) (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 Seawater in the Deep Western Boundary Current (Pickart et al. 1999; MERCINA 2001).

After the NAO index's large drop during 1996, the CSWS shifted to its minimum modal state, with relatively cold and fresh LSSW advancing along the shelf break, displacing ATSW offshore and penetrating to the southwest as far as the Middle Atlantic Bight (Fig. 1b) (MERCINA 2001). In addition to its advance along the shelf break, the LSSW also invaded the deep basins of the Gulf of Maine and Western Scotian Shelf. By early winter 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. By early autumn 1998, the hydrographic properties of the Gulf of Maine deep basins reflected the advective replacement and mixing that had occurred between the invading LSSW and the resident deep waters derived largely from ATSW.

The observed hydrographic changes were short lived, however. The NAO index's large drop during winter 1996 was a single-year event, and the index returned to positive values for the remainder of the late 1990s. 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. As the supply of LSSW to the region decreased, ATSW returned to its previous position adjacent to the shelf break and began supplying slope water to the deep basins of the Gulf of Maine and Western Scotian Shelf. By the end of 1999, hydrographic conditions in these deep basins resembled conditions prior to the NAO-associated modal shift in the CSWS.

Time-series analysis of the NAO index and regional slope water temperature (RSWT) index over the past half century has shown that modal shifts in the CSWS are commonly associated with phase reversals in the NAO (Fig. 2a,b) (MERCINA 2001). During the 1960s, the NAO index was in a predominantly negative phase, and the CSWS exhibited the relatively cold and fresh conditions characteristic of its minimum modal state. From the early 1970s to the present, the NAO index has been predominantly positive, and the CSWS has usually exhibited the relatively warm and salty conditions characteristic of its maximum modal state. Five times during these three decades (1977, 1979, 1985, 1987, and 1996), the NAO index has dropped to negative values for a single year. In each case, the CSWS appears to have responded to a drop in the NAO index by shifting toward its minimum modal state after a 1–2-yr time lag (1978, 1981, 1987, 1989, and 1998). Although the first two responses of the CSWS, in 1978 and 1981, were relatively small, the latter responses were more substantial. The response to the 1985 and 1987 phase reversals in the NAO index involved a multiyear modal shift lasting from 1987 to 1990. The response to the 1996 phase reversal was the most dramatic and most well-documented modal shift to date.

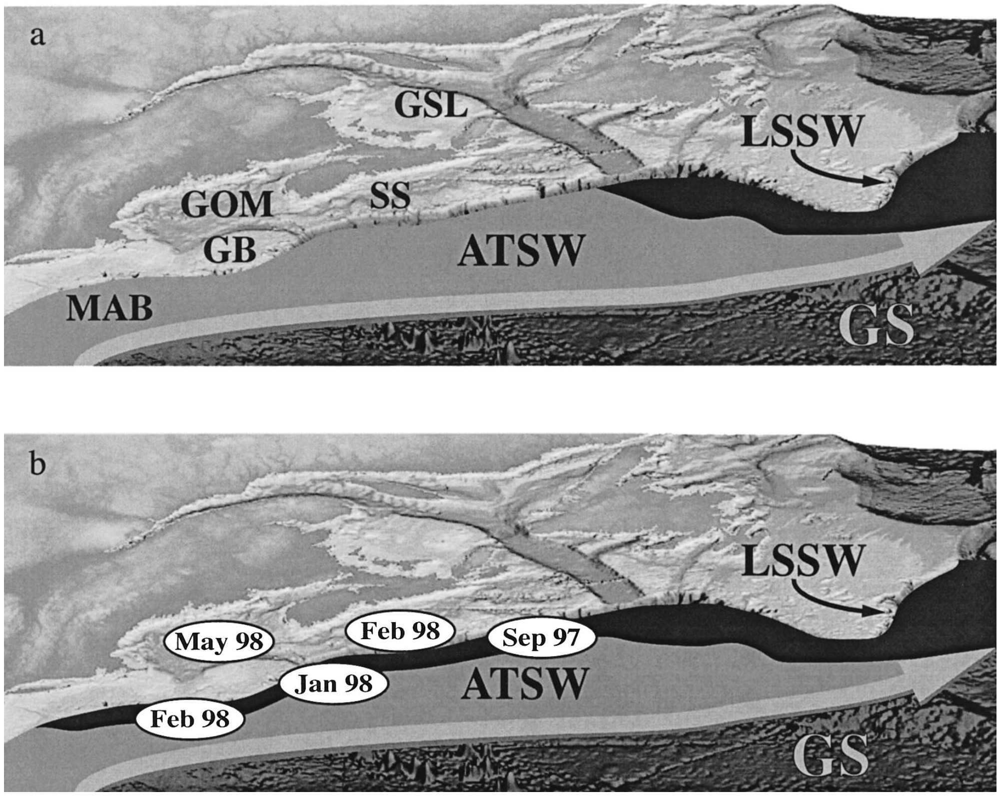

Fig. 1. a) Maximum (a) and minimum (b) modal states of the CSWS. Circled dates indicate the 1997–1998 advance of LSSW frontal boundary along continental shelf break. Geographical features, water masses, and currents are labeled as follows: GB, Georges Bank; GOM, Gulf of Maine; GSL, Gulf of St. Lawrence; MAB, Middle Atlantic Bight; SS, Scotian Shelf; ATSW, Atlantic Temperate Slope Water; LSSW, Labrador Subarctic Slope Water; GS, Gulf Stream.

The 1–2-yr 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 multiple regression model for predicting the modal state of the CSWS (Fig. 3a). The RSWT index serves as an indicator of the model state of the CSWS and for a given year, t, can be predicted from the previous year's values of the NAO index and RSWT index as follows:

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

This model explains a large and significant proportion of the variance observed in the RSWT index time series between 1959 and 2000 ($R^2 = 0.54$; $P < 0.001$). Inclusion, as predictive variables, of NAO and RSWT indices with time lags of 2 and 3 yr did not significantly improve the model's fit to the data. In our mechanistic interpretation of this empirical model, the value of the previous year's RSWT index captures the CSWS's inertia and resistance to change, whereas the value of the previous year's NAO index provides the forcing necessary to shift the system from one modal state to another.

Moving from an explanatory mode to an operational mode, the model also can be used to forecast future values of the RSWT index (Fig. 3b). Operationally, forecasts of the RSWT index_t can be made when the observed NAO index_{t-1} becomes available from the National Center for Atmospheric Research (http://www.cgd.ucar.edu/~jhurrell/nao.html) and when hydrographic data from the hydrographic database of the Bedford Institute of Oceanography (http://www.mar.dfo-mpo.gc.ca/science/ocean/database/data_query.html) become available to calculate the RSWT index_{t-1}. Because the NAO index is based on winter atmospheric pressure data, its value for any given year typically becomes available in late spring of the same year (Hurrell pers comm.). Therefore, the limiting step in forecasting the following year's RSWT index_t typically comes down to finding an appropriate value for the RSWT index_{t-1}. Because the RSWT index_{t-1} that we use is annual, it cannot be calculated until the year is complete. This approach limits forecasts to a lead time of no more than 1 yr. In the future, we will explore how the model's forecasting accuracy is affected when the index is calculated during certain critical periods or seasons within the year. This information may enable us to make earlier forecasts and possibly improve our forecasting skill.

An unusual opportunity for testing the model's forecasting ability arose during the past year. The NAO index_{2001} was negative, only the sixth such occurrence since the early 1970s. From this observation, we predict a likely decline in

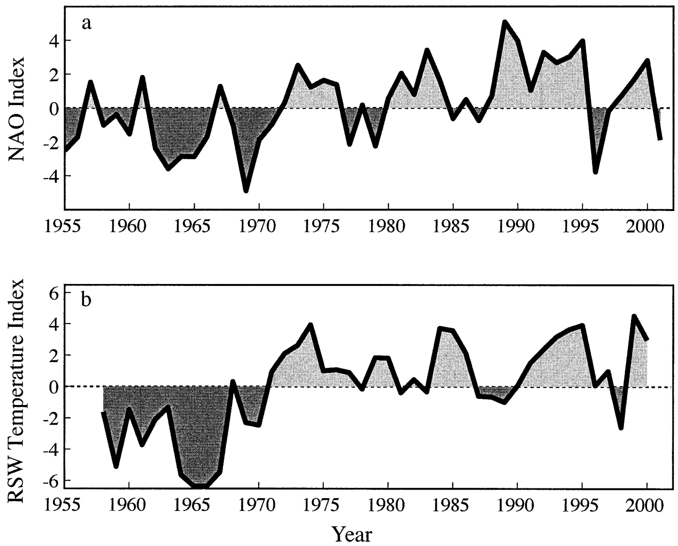

Fig. 2. Time series from the North Atlantic. (a) Annual values of the NAO index. The NAO index is the mean winter-time atmospheric pressure difference anomaly between the North Atlantic's subtropical high-pressure system, measured in Lisbon, Portugal, and the subpolar low-pressure system, measured in Stykkisholmur, Iceland (Hurrell 1995). (b) Annual values of the RSWT index. The RSWT index was developed as an indicator of the modal state of the CSWS, with positive (negative) values corresponding to maximum (minimum) modal state conditions (MERCINA 2001). It is the dominant mode derived from a principal components analysis of eight slope water temperature anomaly time series from the Gulf of Maine/Western Scotian Shelf region. The time series correspond to mean annual slope water temperature anomalies between 150 and 250 m in Emerald Basin, Georges Basin, Jordan Basin, and Wilkinson Basin and from four geographic sectors overlying the region's continental slope. All hydrographic data were derived from the hydrographic database of the Bedford Institute of Oceanography (http://www.mar.dfo-mpo.gc.ca/science/ocean/database/data_query.html). The cross-correlation analysis of the NAO index and RSWT index time series exhibited a significant positive correlation with a time lag of 1 yr ($R^2 = 0.31$; $P < 0.05$) and a nearly significant correlation with a time lag of 2 yr.

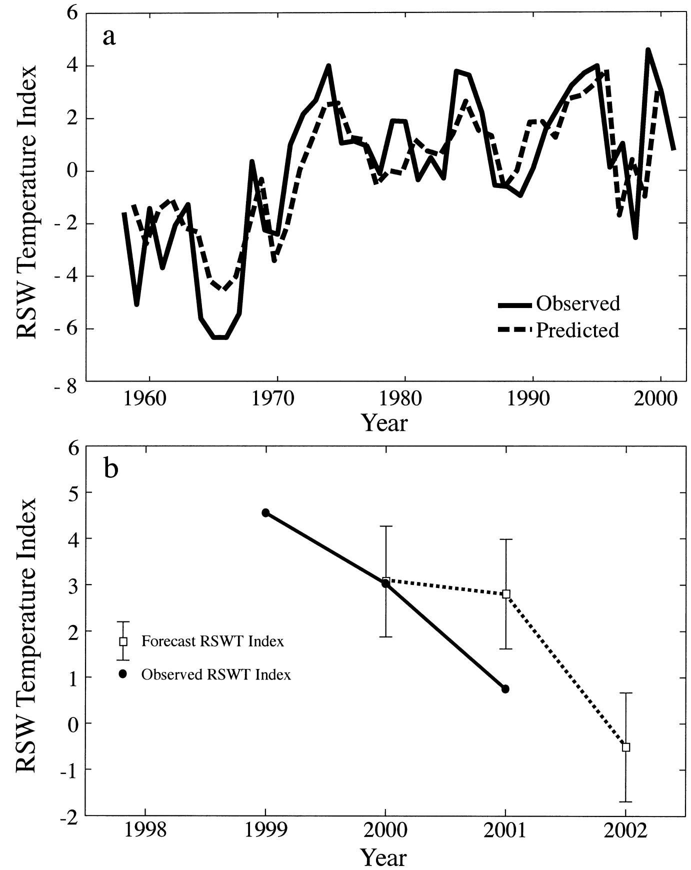

Fig. 3. Observed and predicted time series of the RSWT index. (a) Observed RSWT index time series for 1958–2000 is indicated with solid line; predicted RSWT index time series for 1959–2000 is indicated with dashed line. (b) Forecasts of the RSWT index for 2000–2002. The RSWT index forecasts for 2001 and 2002 are out-of-sample predictions based on a model with parameters fit to the 1958–2000 time-series data. Bars correspond to 95% confidence intervals.

the RSWT index_{2002}, with an 80% probability that the decline will be sufficiently negative to represent a modal shift in the CSWS (Fig. 3b). Looking farther into the future, we can use daily and monthly values of the NAO index, as reported by the NOAA Climate Diagnostic Center (http://www.cdc.noaa.gov/~gtb/tele/nao.gif) and NOAA Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/bulletin/), respectively, and begin to anticipate the likelihood of different outcomes for the RSWT index_{2003}. During early winter 2002, daily and monthly values of the NAO index were strongly negative, suggesting a likely continuation in 2003 of the RSWT index's decline that we predicted for 2002. However, the daily and monthly values of the NAO index abruptly increased and became positive during late winter 2002. Therefore, a continuing decline of the RSWT index in 2003 no longer seems as likely. Because none of the NAO index phase reversals dating back to the early 1970s have lasted for longer than a single year, the return to a positive annual NAO index value in 2002 would be consistent with recent patterns.

Accurate oceanographic forecasting is important to the management and conservation of living marine resources. The modal shifts in slope-water circulation patterns associated with phase reversals in the NAO have large impacts on the ecological dynamics in the NW Atlantic. The copepod species *Calanus finmarchicus,* which typically represents >80% of the region's springtime zooplankton biomass, declined in abundance by more than an order of magnitude in the Gulf of Maine during 1998, a response linked to changes in slope-water circulation patterns brought about by the 1996 drop in the NAO index (Greene and Pershing 2000; MERCINA 2001). Because *C. finmarchicus* is the principal source of nutrition for many planktivorous fish, marine mammals, and seabirds in the region, the effects of altered circulation patterns on the abundance of this species are propagated to higher levels in the food chain. For example, the highly endangered northern right whale, *Eubalaena glacialis,* suffered through 2 yr of physiological stress and poor reproduction in 1999 and 2000 (Kraus 2001) that can be linked to the 1998 decline in *C. finmarchicus* abundance (Greene et al. unpubl. data). In contrast, after the CSWS returned to its maximum modal state in 1999, the *C. finmarchicus* population responded with an order of magnitude increase in abundance (MERCINA 2001, in press), and the northern right whale population returned to good health, producing more calves in 2001 than at any time since records began in 1980 (Kraus 2001; Greene et al. unpubl. data). As observed by Thompson and Ollason (2001), the impacts of climate variability on long-lived top predators may be complex and may involve considerable time lags. As we work out the mechanistic details linking climate variability to the interactions of physical and biological processes in the ocean, our improved forecasting abilities will enhance future efforts to manage and conserve both exploited and endangered marine populations.

Charles H. Greene[1]
Andrew J. Pershing

Ocean Resources & Ecosystems Program
Cornell University
Ithaca, New York 14853

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[1] Corresponding author (chg2@cornell.edu).

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