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Impacts of the North Atlantic Oscillation on sea surface temperature on the Northeast US Continental Shelf

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ABSTRACT

The North Atlantic Oscillation (NAO) is the dominant large-scale atmospheric oscillation in the North Atlantic and has profound effects on water temperatures in the North Atlantic. In this paper we diagnosed the effects of the NAO on sea surface temperature (SST) in the Northeast US Continental Shelf (NES). Waters in the Gulf of Maine (GOM) originate primarily from Scotian Shelf Water (SSW) at the surface and Labrador Slope Water (LSW) and Warm Slope Water (WSW) at depth through the Northeast Channel. By using a high-resolution SST dataset, we found that the correlation between the NAO and annual mean SST in the GOM is significant and negative at lag of four years. Further spatial correlation analysis shows that the NAO influences SST in the GOM primarily through advection of SSW or shelf water at the surface from the Labrador Sea. Cross-correlation analysis was also applied between the NAO and SSTs in other subregions of the NES (Georges Bank, Southern New England, and Mid-Atlantic Bight), but no statistically significant relationships were found at any lags. Different from temperature at depth in the GOM that is positively influenced by the NAO with a lag of two years, we concluded that the NAO has a significant negative effect on SST in the GOM four years later, while its effects on SSTs in the other three subregions of the NES are negligible. The four-year lagged relationship we found between the NAO and annual mean SST in the GOM provides a robust empirical method to predict the effect of the NAO on annual mean SST in the GOM four years in advance.

1. Introduction

The North Atlantic Oscillation (NAO) is the dominant mode of climate variability in the North Atlantic region and has been known to affect ocean temperature as well as ecosystem dynamics in the North Atlantic Ocean (Drinkwater et al., 2003). The NAO index quantifies the status of atmospheric mass shift between the subtropics high pressure and the polar low pressure regions (Hurrell et al., 2001). More specifically, the positive phase of the NAO represents an enhanced pressure gradient between Azores and Iceland, and the negative phase of the NAO represents a reduced pressure gradient between Azores and Iceland.

Variations in NAO-induced wind fields can cause dramatic changes in air-sea heat flux and water momentum (Visbeck et al., 2003). In the Northwest Atlantic, the most significant direct air-sea heat flux forcing caused by the NAO is in the Labrador Sea (Greene and Pershing, 2000; Greene et al., 2013). During positive (negative) phases of the NAO in boreal winter, winds from the relatively cold and dry continent are more (less) intense over the Labrador Sea, leading to enhanced (reduced) heat loss from the Labrador Sea surface and consequently colder (warmer) local seawater in the Labrador Sea. By using a combination of satellite altimetry data with conductivity-temperature-depth observations, Han et al. (2010) found a significant simultaneous relationship between the winter NAO and southward transport of the Labrador Current. Thus, the positive NAO enhances local latent heat loss from the surface as well as advection of the cold Labrador Current in the Labrador Sea, both of which tend to decrease local SST in the Labrador Sea. Greene et al. (2013) suggested that this NAO forced temperature signal in the Labrador Sea then propagates along the outer continental shelf and slope regions of the Northwest Atlantic all the way to the Mid-Atlantic Bight (MAB), creating the remote NAO signal on the downstream Northeast US Continental Shelf (NES), including the Gulf of Maine (GOM).

Waters in the GOM are from two major sources (Mountain and Kane, 2010; Smith et al., 2012). One is the Scotian Shelf Water (SSW) that originates from advection of the Labrador Current along the Northwest Atlantic continental shelf (Drinkwater, 1996). The other is the Slope Water that consists of two different water masses: Warm Slope Water (WSW) and Labrador Slope Water (LSW) (Greene et al., 2013; Mountain, 2012). The relatively warm and salty WSW is influenced by the Gulf Stream and thus

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contributes to the Slope Water system mostly in the eastern slope region, while the relatively cold and fresh LSW originates from the upstream Labrador Current and thus contributes to the Slope Water system mostly in the western slope region. Properties of the Slope Water are primarily determined by the dynamical interplay of these two distinct water masses (Smith et al., 2001).

Compared to the Slope Water, SSW is less dense because of its extreme freshness (~32 ppt) (Mountain, 2012). Hence, when both SSW and the Slope Water enter into the GOM through the Scotian Shelf and the Northeast Channel respectively, SSW tends to stay in upper layer while the Slope Water tends to stay in deep layer (Chapman et al., 1986). The two water masses flow cyclonically in the GOM and then propagate onto the Georges Bank (GB) and turn southwestward toward Cape Hatteras (Drinkwater, 1996; Mountain, 2012). Using stable oxygen-isotope tracer ^{18}O, a conservative tracer in seawater with strong latitudinal gradient, Chapman et al. (1986) analyzed the contribution of SSW in seven inshore–offshore oriented vertical shelf transects located from the Northeast Channel in the North to the Chesapeake Bay in the South. They found that surface waters from the GOM to MAB are dominated by SSW, except in the deep offshore regions where the Slope Water is also evident and in some narrow nearshore surface regions where local freshwater runoff also contributes a measurable percentage. The results of Chapman et al. (1986) demonstrate the continuity of the surface flow from the Scotian Shelf to MAB, as well as the crucial role of SSW in surface waters on the NES. They also showed that the continuity of this mean flow was stable in various seasons.

Mountain (2012) investigated the effects of the NAO on composition of the Slope Water entering into the GOM through the Northeast Channel at depth. Previous studies have shown that westward intrusion of LSW is modulated by the phase of the NAO, namely the positive phase of the NAO causes reduced transport of LSW into the Northeast Channel and vise versa (Drinkwater et al., 1998; Han et al., 2014; Pershing et al., 2001). Its dynamical explanation is that in the positive phase the NAO forces the subpolar gyre to expand northward so the baroclinic component of the Labrador Current at the Labrador Sea shelf break is weakened, resulting in a reduction in the westward transport (Greene et al., 2013). Mountain used a 3-point mixing method of temperature–salinity relationships to assess annual mean percentage contribution of LSW in the Northeast Channel at 150–200 m depth. A significant negative correlation between boreal winter (December–March) mean NAO index and the annual mean percentage contribution of LSW in the Northeast Channel at depth was found, with LSW lagging the NAO by two years. Pershing et al. (2001) found a positive correlation between the NAO and annual mean slope water temperature anomalies at 150–200 m depth in the continental slope region (which is quantified as the Regional Slope Water Temperature Index) with slope water temperature lagging the NAO by one year, supporting the negative relationship between the NAO and the percentage contribution of LSW in the Northeast Channel at depth. The difference in the time lags may be understood if it takes one year for the NAO signal to cause temperature change in the Slope Water system and another year for this temperature signal in the Slope Water system to propagate at depth into the Northeast Channel. Several studies have shown that bottom temperature changes on the Scotian Shelf and in the GOM are profoundly influenced by advection of LSW (Drinkwater and Gilbert, 2004; Petrie, 2007; Petrie and Drinkwater, 1993). Specifically, increased flow of LSW promotes onshore intrusion of the Slope Water at depth on the Scotian Shelf and in the GOM that leads to decreases in bottom temperature in these two regions. Therefore, the negative relationship between the NAO and the percentage of LSW in the Northeast Channel at depth with a lag of two years (Mountain, 2012) indicates that the positive (negative) NAO can lead to increase (decrease) in bottom temperature in the GOM with temperature changes lagging the NAO by two years.

Sea Surface Temperature (SST) of the NES exhibits the largest interannual variability in the North Atlantic (Petrie and Drinkwater, 1993). This paper investigated how the NAO affects SSTs on the NES by using a high resolution SST dataset. It is well established that the NAO influences the temperature at depth in the GOM primarily through influencing its major water source, namely the Slope Water, at depth. Our study seeks to examine whether or not the NAO influences SSTs in the GOM and other parts of the NES primarily through influencing SSW, which according to Chapman et al. (1986) is the major water source of the NES at the surface.

2. Data and methods

In order to clarify the connection between the NAO and SST in the GOM, the NOAA Optimum Interpolation Sea Surface Temperature (OISST) version 2 high resolution dataset (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.highres.html) was used over the period of 1982 to 2010. The OISST provides daily SST with high spatial resolution of 0.25° latitude × 0.25° longitude (Reynolds et al., 2007) that is needed to sufficiently resolve shelf regions like the NES. The dataset uses *in situ* observations from ships and buoys to correct biases in satellite remote sensing data. Annual mean SST values were calculated in each grid by averaging the daily OISST dataset. The monthly NAO index provided by NOAA is calculated based on applying the Rotated Principle Component Analysis (RPCA) to monthly standardized 500-mb height anomalies (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml), and the December–March (DJFM) mean NAO index was calculated for this research. The subsurface ocean temperature at depth is from NCEP Global Ocean Data Assimilation System (GODAS) that is developed by the ESRL PSD (http://www.esrl.noaa.gov/psd/). The dataset provides real-time global ocean assimilated monthly 3D potential temperature since 1980, with horizontal resolution 0.333° latitude × 1° longitude and 40 vertical levels at depth from 5 m to 4478 m, with 10 m resolution in the upper 200 m.

Pearson correlations were calculated between the NAO and annual mean SST in each NES subregion to identify any significant relationships between the NAO and lagged SSTs on the NES. According to distinct geological, hydrological, and biological characteristics, the NES can be divided into four subregions from south to north: MAB, Southern New England (SNE), Georges Bank (GB), and GOM (Clark and Brown, 1977). The off-shore boundary of these four subregions is delineated by the 200 m isobaths of the continental shelf (Fig. 1). Details of ocean circulation pattern for the Northwest Atlantic including the NES can be found in Greene et al. (2013). To make a direct comparison with the results of Mountain (2012), the Pearson correlation method was also used between the NAO and annual mean SST in box M (see Fig. 1), where a positive relationship between the NAO and the percentage of LSW at 150–200 m depth was found, with LSW lagging the NAO by two years.

3. Results

Average SSTs in both box M and the GOM had significant interannual variability and notable changes in trend (Fig. 2). From 1982 to 2010, the interannual fluctuations of the two SST time series were similar, with a correlation coefficient of 0.93, and both of them had cooling trends before ~1992, and warming trends thereafter.

Mountain (2012) found a two-year lag between the NAO and the annual mean percentage of LSW in deep water at 150–200 m