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Labrador slope water entering the Gulf of Maine—response to the North Atlantic Oscillation

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ABSTRACT

The percent of Labrador Slope Water (%LSW) in the waters entering the Gulf of Maine at depth (150–200 m) through the Northeast Channel is estimated from temperature/salinity measurements for the period 1964–2008. Comparison of the annual average %LSW with the North Atlantic Oscillation (NAO) lagged two years shows that both series have very similar, but opposite, long term trends. High %LSW in the 1960s decreased to low values in the 1990s as the NAO increased from low to high values over the same period. A regression of the residuals of the two series from their long term trends also is significant at the 5% level, indicating that the %LSW at the Northeast Channel has a persistent relationship on a year-to-year basis with the NAO over the full range of variation in the NAO. The response of the %LSW to the NAO, however, appeared substantially reduced after about 1990. Changes in the potential nutrient flux into the Gulf of Maine/Georges Bank system associated with changes in the %LSW cannot account for changes in chlorophyll a concentrations estimated for three multi-year stanzas during the sampling period.

1. Introduction

The waters in the Gulf of Maine come from two major sources. The first is relatively cold and fresh waters from the Scotian Shelf, called Scotian Shelf Water (SSW), that enter in the surface layers around Cape Sable. The second is warmer, more saline waters from the slope region offshore that enter at depth through the Northeast Channel, called Slope Water (Smith et al., 2001). The waters from these two sources mix as they circulate around the Gulf and form the waters that enter onto Georges Bank and become the primary component of the shelf water in the Middle Atlantic Bight to the west. Between Cape Hatteras and the Grand Banks the Slope Water itself is comprised of two different water masses (McLennan, 1957; Gatien, 1976). The first is Warm Slope Water (WSW) whose properties are influenced by the Gulf Stream and is dominant in the western part of the slope region. The second is Labrador Slope Water (LSW) that derives from the Labrador Current system and is dominant in the eastern part of the slope region. The two types of slope water can be distinguished in a temperature/salinity analysis because the LSW is colder and fresher than the WSW.

The spatial distribution of WSW and LSW in the slope region has been observed to shift and change the character of the slope water entering the Gulf of Maine. Worthington (1964) identified a cooling of the slope water south of Nova Scotia in 1959 and attributed it to a westward extension of Labrador waters caused by atmospheric forcing associated with unusually high pressure over the Greenland/Iceland region (i.e., a decrease in the strength of the Icelandic low). Colton (1968) identified a cooling of the water temperatures at 200 m in the Gulf of Maine and along the nearby continental slope from the late 1950s to early 1960s and similarly attributed the cooling to an encroachment of waters of Labrador origin. Looking over a longer period (1945–1990) Petrie and Drinkwater (1993) showed the dominant regional change in water properties was the cooling and freshening of the deep waters in the basins along the Scotian Shelf and in the Gulf of Maine from the early 1950s to the mid-1960s. Through a simple model they also showed that the changes were quantitatively consistent with an increased westward transport of Labrador Current waters. Drinkwater et al. (1998) tracked the progressive westward extension of LSW along the edge of the Scotian Shelf during late 1997 and into the Gulf of Maine through the Northeast Channel in January 1998. They attributed the event to increased transport of the Labrador Current system associated with a large decrease in the North Atlantic Oscillation (NAO) in 1996, with an approximate two year time lag between the NAO decrease and the arrival of LSW properties at the Northeast Channel. They also pointed out that the cold conditions in the late 1950s and early 1960s identified by Worthington (1964), Colton (1968) and Petrie and Drinkwater (1993) occurred during an extended period of low

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NAO conditions. Petrie (2007) compared coastal bottom water temperatures from Labrador to the Gulf of Maine with variations in the NAO and found that to the north (Labrador and Newfoundland) the temperatures were cooler (warmer) during periods of high (low) NAO and were the opposite on the Scotian Shelf and in the Gulf of Maine. He concluded that the temperature changes in the north were caused by local forcing (cold air conditions during high NAO) and in the southern areas by advection of Labrador Slope Water.

The dynamical explanation for the NAO-LSW relationship suggested by Drinkwater et al. (1998) was that during a low NAO the Labrador Current system is strengthened and the transport of Labrador water westward from the Grand Banks is increased. This explanation was subsequently supported by hydrodynamic modeling. Marsh (2000) forced a general circulation model of the North Atlantic with the atmospheric conditions during the low NAO period of 1878–1881. Relative to a control model run, during the low NAO conditions the Labrador Current transport increased and water with Labrador properties extended westward around the Tail of the Bank. Off the Scotian Shelf temperature anomalies of -2 °C occurred at 100–200 m depth in the modeled spring of 1882. The model results provide an explanation for the observed low water temperatures believed responsible for a high mortality of tilefish along the shelf edge off the Middle Atlantic Bight in 1882, as described by Marsh et al. (1999).

The westward extension of LSW is only one aspect of the slope region's response to changes in the NAO. The north-south movement of the Gulf Stream also exhibits a close relationship to the NAO, again with about a two year lag (Taylor and Stevens, 1998). The movement is believed dynamically associated with the decrease-increase in the transport of LSW around the Tail of the Bank (Rossby, 1999).

The rate of slope water transport into the Gulf of Maine also has been shown to vary. Direct measurements made from 1993–1996 (Smith et al., 2001) 1976–1978 revealed slope water transport half that measured from 1976–1978 (Ramp et al., 1985). The SSW transport in the earlier period was estimated to be about half that in the later period, such that the total flux into the Gulf was approximately the same in both periods (Smith et al., 2001). More recent measurements in the Northeast Channel (2004–2008) have indicated a further reduction in the slope water influx, with prolonged periods of outflow from the Gulf (Smith et al., in press). The likely cause of the decadal-scale decreases in slope water inflow is believed to be an increase in transport SSW along the Scotian Shelf and into the Gulf of Maine resulting in a rise in coastal sea level and an associated offshore pressure gradient that opposes the inflow of slope water at depth through the Northeast Channel (Smith et al., in press).

The shift in the contribution of WSW vs. LSW entering the Northeast Channel has potentially important implications for the productivity of the Gulf of Maine/Georges Bank system. The slope water entering through the Channel is believed to be a primary source of new nutrients supporting that biological system (Schlitz and Cohen, 1984); and the nutrient concentrations in LSW are about one third lower than those in WSW (Townsend, 1998). Steele et al. (2007) modeled the Georges Bank ecosystem in different multi-year stanzas over the past half century and concluded that the system's fish production during the early 1960s was lower than in recent decades. They hypothesized that the lower production might have been due to a decrease in the supply of nutrients to the system resulting from the shift to LSW entering the Gulf, as documented by Petrie and Drinkwater (1993).

The purpose of this report is to document the history of LSW entering the Gulf of Maine and its relationship to the NAO on a year-to-year basis. The relationship between the LSW history and observed variations in the productivity of the Gulf of Maine/Georges Bank system also is considered.

2. Data and methods

To identify the character of slope water entering the Gulf of Maine, the average temperature and salinity over the depth range 150–200 m was determined for a region just inside the Northeast Channel (Fig. 1) over the period 1964–2010. Hydrographic observations within the region were obtained from the World Ocean Database (http://www.nodc.noaa.gov/OC5/WOD09/pr_wod09.html, last accessed on 05/06/2012), the Bedford Institute of Oceanography hydrographic database (http://www.bio.gc.ca/science/data-donnees/base/index-eng.php, last accessed on 04/30/2012) and from the Northeast Fisheries Science Center of NOAA/NMFS, which makes hydrographic measurements as part of its regional monitoring activities. For each hydrographic profile temperature and salinity observations were linearly interpolated to one meter intervals and averaged over the 150–200 m layer. Because data during the earlier years were largely from bottle casts, to be accepted a profile had to have at least one temperature/salinity pair between 130–150 m and one pair between 200–220 m in order to appropriately bracket the layer of interest. In addition temperature and salinity values at 150 m and at 200 m also were retained to consider changes in properties over the layer. In total 745 profiles were obtained, for an average of about 16 profiles per year within the region. Yearly temperature and salinity values were calculated by averaging all of the observations within a year—for the 150–200 m layer, at 150 m and at 200 m.

The observed temperature and salinity within the region are assumed to result from a 3-point mixing of WSW, LSW and SSW, with the latter mixing from above (Fig. 2). The characteristic temperature and salinity values used are 12 °C and 35.4 for WSW, 6 °C and 34.6 for LSW, and 2 °C and 32.0 for SSW. These values were determined, respectively, from Petrie et al. (1996, box #63), Drinkwater and Trites (1986, box #26) and Petrie et al. (1996, boxes #23-24). All of the annual 150–200 m temperature/salinity

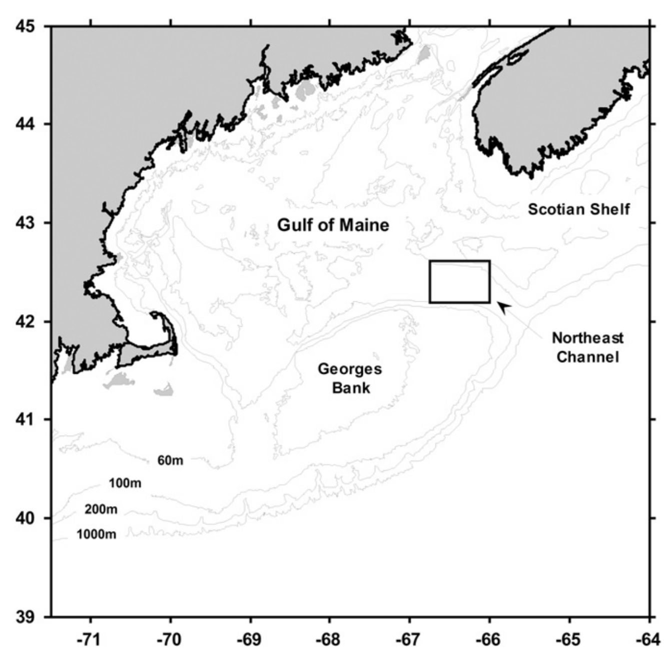

Fig. 1. Gulf of Maine Region. The box just inside the Northeast Channel indicates the area within which the hydrographic properties were averaged.