Water Masses and Nutrient Fluxes to the Gulf of Maine

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ABSTRACT

The Gulf of Maine, a semi-enclosed basin on the continental shelf of the northwest Atlantic Ocean, is fed by surface and deep water flows from outside the Gulf: Scotian Shelf Water from the Nova Scotian shelf that enters the Gulf as a surface layer, and Slope Water that enters at depth and along the bottom through the Northeast Channel. There are two types of Slope Water, Labrador Slope Water (LSW) and Warm Slope Water (WSW), the proportional volume fluxes of which alternate in relative importance; it is these deep water masses that are the major source of dissolved inorganic nutrients to the Gulf. It has been known for some time that the volume inflow of Slope Waters of either type that enters the Gulf of Maine is variable, that it has been observed to negatively co-vary with the magnitude of inflowing Scotian Shelf Water at the surface, and that periods of greater inflows of Scotian Shelf Water have become more frequent in recent years, accompanied by reduced Slope Water inflows. We present here analyses of a ten-year record of data collected by moored sensors in Jordan Basin, in the interior Gulf of Maine, and in the Northeast Channel, along with recent and historical hydrographic and nutrient data, that help reveal the nature of Scotian Shelf Water and Slope Water inflows, and in particular, their influence on the deep and bottom waters of the Gulf of Maine. Volume fluxes of nutrient-rich Slope Waters and nutrient-poor Scotian Shelf Waters alternate episodically with one another on time scales of months to several years, creating a variable nutrient field, upon which the biological productivities of the Gulf of Maine and Georges Bank depend. Unlike decades past, the inflows of Slope Waters of either type do not appear to be correlated with the North Atlantic Oscillation, which had been earlier presupposed to influence the relative proportions of the two Slope Waters, WSW and LSW, that enter the Gulf. We suggest that of greater importance today may be the recent increases in Arctic melting and accompanying freshwater fluxes to the Labrador Sea which intensify the volume transport of the inshore, continental shelf limb of the Labrador Current and its continuation as the Nova Scotia Current. The result is more frequent, episodic fluxes of colder, fresher, less dense, and low-nutrient SSW into the Gulf of Maine.

Key Words: Gulf of Maine, water masses, nutrients, Labrador Slope Water, Warm Slope Water, Scotian Shelf Water, moored sensors, North Atlantic Oscillation

1. Introduction

Of great importance to the level of biological productivity of shelf seas is the supply of dissolved inorganic nutrients, either from the landward or the seaward end member. Because biological productivity in the oceans generally falls off with distance from shore, conventional wisdom once held that nutrient fluxes were from the land (e.g., Ketchum and Keen, 1955); but, this view changed following Riley's (1967) suggestion, based on a mathematical model, that the more likely source is from offshore waters. That the main source of nutrients is indeed from offshore was first confirmed by Fournier et al. (1977) for the Nova Scotian Shelf; they showed that the flux of dissolved inorganic nutrient loads is dominated by cross-isobath flows of deep Slope Waters onto the shelf. In the Gulf of Maine, which receives waters from outside the Gulf both at the surface and at depth (Bigelow, 1927), we now know that the main source of nutrients is also from offshore, with the deep Slope Water flows carrying the bulk of nutrients that drives the biological productivities of both the Gulf and Georges Bank (Schlitz and Cohen, 1984;

Townsend, 1991; 1998; Townsend and Pettigrew, 1997; Hu et al., 2008). But, as we discuss in this communication, those flows of offshore waters are more complex than once thought and may be undergoing important changes in recent years (Pettigrew et al., 2008, 2011; Townsend et al., 2010; Smith et al., 2012).

a) The Gulf of Maine

The Gulf of Maine is a continental shelf sea on the east coast of North America, which is relatively isolated from the North Atlantic Ocean by a series of shallow offshore shoals and banks: Nantucket Shoals, Georges and Browns Banks, and the Southwest Nova Scotian Shelf (Figure 1). Communication between the Gulf's deeper waters and the northwest Atlantic Ocean is mostly confined to the narrow Northeast Channel between Georges and Browns Banks, which has a sill depth of approximately 220 m. Bigelow (1927) pointed out that in addition to the inflows of deep and bottom waters through the Northeast Channel (he used the term "Eastern Channel") there are significant inflows of shelf waters though the shallower "Northern Channel" between Browns Bank and Cape Sable (depth ca. 150 m; Figure 1) such that the Gulf of Maine receives waters both at the surface and at depth in a flow-through fashion. Scotian Shelf Waters enter the Gulf as a cold and relatively fresh surface layer from the Nova Scotian Shelf, and warmer, saltier and denser Slope Waters penetrate the Gulf at intermediate depths and along the bottom through the Northeast Channel. A key feature of the physical oceanography of the Gulf of Maine is the three layered structure that results as these Slope Water and Scotian Shelf Water masses are modified inside the Gulf by seasonal warming and cooling, and by tidal mixing (Hopkins and Garfield, 1979). We can summarize these processes as follows: Deep and bottom waters, of Slope Water origin, enter the Gulf through the Northeast Channel (Bigelow, 1927; Ramp et al., 1985; Smith et al., 2001); this Slope Water layer is commonly defined by salinities greater than 34 ‰ and, once inside the Gulf, may, at times, extend upward from the bottom to depths of less than 75 m (Bigelow, 1927). Additional inflow to the Gulf occurs as a surface layer of cold and relatively fresh Scotian Shelf Water that enters from the east and around Cape Sable, Nova Scotia, as a continuation of the Nova Scotia Current (Smith, 1983; 1989). Sandwiched between these two layers in the interior Gulf seasonally resides an intermediate water layer: convective sinking and mixing of surface waters the previous winter produces relatively cold water temperatures at depths between about 50 and 100 m, which subsequent seasonal warming at the surface isolates as a cold intermediate water layer that slowly erodes during the remainder of the year (Hopkins and Garfield, 1979).

The dense Slope Waters that enter the Gulf spill into the three main basins, Georges, Jordan, and Wilkinson Basins, producing a density field that drives a Gulf-wide baroclinic circulation, the general features of which (e.g., Fig. 2) were first described by Bigelow (1927) and were later refined by Brooks (1985) and others (e.g., Pettigrew and Hetland, 1995; Beardsley et al., 1997; Pettigrew et al., 2005). Overall, the circulation in the Gulf can be described as a cyclonic, or counter-clockwise, gyre system of currents around the Gulf, with cyclonic sub-gyres over the two eastern basins, Jordan Basin and Georges Basin. Rimming the Gulf is a system of coastal currents, including the Eastern Maine Coastal Current (along the Maine coast east of Penobscot Bay) and the Western Maine Coastal Current (west of Penobscot Bay and extending to coastal waters off Massachusetts), that flow east to west, and which are augmented by freshwater discharges from rivers. Details of these coastal currents are given in Pettigrew et al.

(2005). The circulation on Georges Bank is anti-cyclonic (clockwise), and is driven by both density gradients, and by topographic rectification of tidal currents (Loder, 1980; Lynch and Namie, 1993, Xue et al, 1998).

b) Slope Waters

The flow of Slope Water through the Northeast Channel and into the Gulf of Maine has been known since Bigelow (1927), but it was not recognized until much later that those Slope Waters are the major source of dissolved inorganic nutrients, both to the Gulf of Maine and to Georges Bank (Schlitz and Cohen, 1984; Townsend, 1991; 1998; Townsend and Pettigrew, 1996; Townsend et al., 2006; Hu et al., 2008; Townsend and Ellis, 2010; Rebuck, 2011). Once in the Gulf, deep nutrient-rich waters are brought to the surface by a number of physical processes, including Ekman upwelling, vertical mixing by tides and long gravity waves, and, especially, winter convective overturning, which sets the stage for the annual winter-spring phytoplankton bloom across much or all of the Gulf's area (Thomas et al., 2003; Rebuck, 2011; Rebuck and Townsend, 2014). Vertical mixing by tides occurs throughout the year and mixes deep water nutrients into the tidally-mixed surface waters off southwest Nova Scotia, in the eastern Maine-Grand Manan Island area, around the edges of the mouth of the Bay of Fundy, and along the Northern Flank of Georges Bank. Those nutrients are then advected horizontally with the residual surface circulation (e.g., Townsend et al., 2014).

The Slope Water that enters the Gulf of Maine was once thought to be a single water mass, defined by its temperature and salinity properties (Bigelow, 1927; McLellen et al., 1953), but Gatien (1976) showed that it is actually made up of two components: Warm Slope Water and Labrador Slope Water. Warm Slope Water (WSW) is a warm and salty water mass in the upper 300 to 400 m that is generally located north and west of, and adjacent to, the Gulf Stream, and sits atop deep North Atlantic Central Water (NACW). WSW is the product of mixing among Gulf Stream water, NACW, and coastal (shelf) waters, and flows in a general northeast direction adjacent to the Gulf Stream (Fig. 3). It is characterized by its warm temperatures and high salinities (Gatien, 1976), and high nutrient concentrations (Townsend and Ellis, 2010) below the surface, which are from deep NACW. Labrador Slope Water (LSW) is a deeper water mass that resides shoreward of, and beneath, WSW and coastal shelf waters; it generally flows to the southwest as a continuation of the offshore, continental slope component of the Labrador Current. Water properties of LSW are characterized by colder temperatures and slightly lower salinities (Gatien, 1976), and significantly lower nutrient concentrations than WSW (Townsend et al., 2006; Townsend and Ellis, 2010). Both water masses reside in the Slope Sea, an elongated triangular-shaped area bounded by the continental shelf to the northwest, the Gulf Stream to the south, and to the east by that portion of the Grand Banks known as "the tail of the Bank" (Fig 3). Both Slope Water types, along with Shelf Waters, enter the Gulf of Maine in varying proportions to one another, and become mixed as they flow throughout the Gulf (Drinkwater et al., 1998).

Changes in inflows of deep Slope Waters through the Northeast Channel have been documented by Smith et al. (2001; 2012) and Pettigrew et al. (2008; 2011) based on moored current meter records. The flow of waters through the Northeast Channel has historically been assumed to be directed into the Gulf at all depths on the eastern side of the Channel and out of the Gulf on the western side at shallow and intermediate depths, but with an overall net positive flow directed into the Gulf, thus supplying the Gulf with high salinity, nutrient-rich waters. Smith et al. (2001), however, showed that inflows of Slope Waters were reduced during periods of enhanced inflows of Scotian Shelf Waters at the surface in the Northeast Channel area and in the "Northern Channel" between Cape Sable, N.S., and Browns Bank. They showed that the Scotian Shelf Water inflow during the period 1995-1996 increased by a factor of two, while the inflowing Slope Water was reduced by about half. Pettigrew et al. (2008; 2011) and Smith et al. (2012) showed that the flow pattern in recent years is characterized by fall and winter episodes of greater outflow of deep waters through the Northeast Channel, hypothesized to be in mass balance response to a greater volume transport of shelf water from the Nova Scotian Shelf into the Gulf of Maine. That influx to the Gulf of fresher (and lower-nutrient) Scotian Shelf Water creates a barotropic pressure gradient that may limit deep flow into the Gulf of its high-nutrient deep and bottom waters. While the inflow of Scotian Shelf Water to the Gulf generally peaks in the winter-spring (Bigelow 1927; Smith 1983; 1989), Smith et al. (2012) showed that these influxes are nonetheless episodic and hypothesized that these are associated with variations in coastal sea level in Nova Scotia. Additionally, the observed trend in sea surface height anomaly, derived from multi-mission satellite altimetry from 1992-2008, shows a contrast in sea level trend between the slope and offshore which implies an accelerated westward flow and thus an increased mass flux from further upstream (Smith, 2012).

Of particular importance to the biological oceanography of the region is the impact of altered Slope Water inflows on the delivery of nutrients to the Gulf of Maine and Georges Bank, which happens in two ways. First, periods of reduced Slope Water inflows and concomitant greater Scotian Shelf Water inflows as shown by Pettigrew et al. (2008,2011) and Smith et al. (2012) will result in an overall reduction in the total nutrient flux to the Gulf. Second, alternating proportions of one Slope Water type or the other that enters the Gulf (LSW versus WSW) can be important because the two differ significantly in their nutrient loads: Nitrate concentrations are much higher in WSW than LSW (> 23 µM in WSW versus 16-17 µM in LSW), while silicate concentrations range from 10-14 µM, with WSW higher by about 10% (Townsend et al., 2006; Townsend and Ellis, 2010). In both Slope Waters, nitrate concentrations exceed silicate by 5-10 µM. The relative proportions of each of these three water masses are therefore important to both the magnitude, and the nature (species composition) of plankton production (e.g., McGillicuddy et al., 2011) in the Gulf as well as on Georges Bank, which receives its nutrient fluxes from the interior Gulf of Maine (Townsend and Pettigrew, 1996; Hu et al., 2008).

We report here an analysis of ten years worth of mooring data from the University of Maine Ocean Observing System (UMOOS) along with recent and historical hydrographic and nutrient data that help to illustrate more clearly the nature of the three water masses, Scotian Shelf Water, Warm Slope Water and Labrador Slope water, of which inflows to the Gulf of Maine vary in an episodic fashion, thus creating variable water properties and dissolved inorganic nutrient loads.

2. Data and Observations

Results reported here are based primarily on mooring (buoy) data collected by the University of Maine Ocean Observing System (UMOOS; www.umoos.org), which is a component of the Northeast Regional Association of Coastal Ocean Observing Systems (NERACOOS; http://www.neracoos.org/). Our focus was on data collected between late 2003 and early 2014 at Buoy M of the Gulf of Maine array, located in Jordan Basin at the position given in Figure 1 (43° 29.41´N, 67° 52.79´W); bottom depth at the mooring site is 285 m. In addition to meteorological data collected at the surface, the mooring has Sea Bird temperature and salinity sensors at depths of 1, 20, 50, 100, 150, 200 and 250 m. The data are transmitted to shore real-time where they are served on the web (http://www.umoos.org/buoyhome.php). Those data are compared with data collected at depths of 100, 150 and 180 m at Buoy N, located at the entrance to the Gulf of Maine on the eastern side of the Northeast Channel. Details of the University of Maine Ocean Observing System are given in Pettigrew et al. (2011). Additional archived hydrographic and nutrient data are also examined (http://grampus.umeoce.maine.edu /nutrients/; Rebuck, 2011), as are hydrographic profiles at stations sampled in the Gulf of Maine by NOAA's EcoMon Program in November 2013.

The Gulf of Maine offshore moorings are replaced for servicing annually. During the summer of 2013 (26 June) Buoy M in Jordan Basin was replaced, at which time we added a Satlantic ISUS optical nitrate sensor at a depth of 100 m (where there is also a Sea Bird temperature and salinity sensor); the ISUS was programmed to collect five data (nitrate) scans (over a period of a few seconds) every 4 hours, which were then averaged to give 6 nitrate measurements per day.

The Jordan Basin mooring site was chosen because of its location in the interior Gulf of Maine. Our intent was to monitor changes in the nitrate concentrations with changes in water properties (temperature and salinity) to determine the relative proportions of Shelf Waters and the two Slope Water types, WSW and LSW, as they contribute to the nutrient field. We ruled out focusing on the UMOOS Buoy N in the Northeast Channel because it is known that not only do nutrient-rich Slope Waters enter the Gulf there, but those entering waters may exit as well, prior to their being delivered to the internal Gulf of Maine, as part of a cyclonic gyre system of surface and deep currents in Georges Basin (e.g., Fig. 2; Smith et al., 2012).

We selected the depth of 100 m to mount the ISUS nitrate sensor on the Jordan Basin mooring based on the assumption that such waters are shallow enough to be mixed during winter convection, thus contributing to the surface nutrient field that fuels the annual spring phytoplankton bloom. Additionally, 100 m is sufficiently deep that seasonal warming and local river runoff are unlikely to confound water properties and our interpretations of water masses. Finally, nutrients at 100 m depth in the Jordan Basin are too deep to be taken up by phytoplankton during the remainder of the year (except via vertical diffusion to shallower depths), and therefore nitrate concentrations there provide a third semi-conservative water property (with temperature and salinity). However, those waters are still shallow enough to be mixed upward by tides into surface waters in the northeastern Gulf, in the eastern Maine-Grand Manan Island area, where nutrient injections can be advected with the Eastern Maine Coastal Current into the main body of the Gulf (e.g., Townsend et al., 1987, and Brooks and Townsend, 1989). In sum, water properties at 100 m in Jordan Basin best represent the nutrient reservoir that drives the biological productivities of the Gulf of Maine and Georges Bank.

Prior to its deployment, the ISUS nitrate sensor was calibrated in the laboratory against nitrate standards verified using a Bran-Luebbe Autoanalyzer. In addition, we collected ground-truth water samples for nutrient analyses from 100 m in Jordan Basin at the time of the mooring redeployment (26 June 2013: $[NO_3^-]$ = 12.24 μM), and again on two other occasions: Once, during a hydrographic survey as part of another study (4 August 2013; two samples collected at 100 m within ~5-10 km of the mooring; $[NO_3^-]$ = 14.98 and 12.62 μM) and during a NOAA Northeast Fisheries Science Center EcoMon Program survey cruise that sampled water from 100 m at a station directly beside the mooring (23 November 2013; $[NO_3^-]$ = 14.43). We also present profiles at stations sampled in Georges Basin and the Northeast Channel during that same NOAA survey cruise. The ISUS sensor failed in early December 2013, after nearly 6 months of reporting real-time data.

3. Results

Mooring records of temperature, salinity and density (sigma-t) for the Jordan Basin buoy (Buoy M) for the 10+ year period from 9 July 2003 to 10 March 2014 are given in Figure 4 (for depths of 250 and 200 m) and Figure 5 (for depths of 150 and 100 m). The water properties at 200 and 250 m reveal a number of irregularly spaced (in time) oscillations, with temperatures fluctuating by as much as 4 °C (between ca. 6 and 10 °C), salinity by as much as 1 ‰ (between ca. 33.7 and 34.7 ‰), and sigma-t by about 0.4 $g \cdot kg^{-1}$; the ranges are slightly greater for the shallower depth (200 m). However, the temperature, salinity and density values at both depths tracked one another closely as each depth exhibited periods of warmer temperatures and higher salinities, alternating with periods of cooler temperatures and fresher salinities.

Data from UMOOS buoy observations since 2003 show that the temperature and salinity characteristics at 200 and 250 m in Jordan Basin are dominated by inter-annual variability. There were several periods of less than one year duration of clearly distinct phases, or episodes, of either warmer and saltier or cooler and fresher water properties, as well as longer duration episodes lasting a year, two years, and a final episode of generally warmer and saltier water properties that began in late 2009 and lasted to early 2014, when the record ends. The data record begins in 2003 with relatively cold and fresh water properties at 200 and 250 m, which abruptly changed to a period of warmer, saltier properties that lasted about 6 months into the spring of 2004. Later in 2004 and again in 2005 there was a pair of relatively brief periods (ca. 3-5 months) of very cool and fresh waters at both 200 and 250 m (<7 °C and <33.75 ‰) separated by a brief period of 3 to 5 months of slightly higher temperatures and salinities. During the two year period from the summer of 2005 to spring-summer of 2007 there was an episode of warmer and saltier waters at both depths, followed by a drop in temperature and salinity that lasted about two and a half years. At that point, in the latter half of 2009, there began an extended period of increasing temperatures and salinities, reaching a peak in January 2011. This last warm and salty episode, while fluctuation some, has lasted to the present (early 2014).

Also shown in Figure 4 is a plot of the North Atlantic Oscillation (NAO) winter index (Dec-Mar) that has been lagged two years. That is, the value of the NAO winter index for the winter of 2002, for example, is plotted as the year 2004, in order to compare water properties two years later. Those data show no correlation with the 200 and 250 m temperature and salinity record over this 10 year period. This was unexpected, because it has already been shown by a number of workers (reviewed in Drinkwater et al., 1998; Pershing et al., 2001; Green and Pershing, 2003; Drinkwater et al., 2003; Petrie, 2007; and Mountain, 2012) that the relative contribution of the two Slope Water types, WSW and LSW, vary with the NAO. That is, the NAO, which is a phenomenon of fluctuating differences in atmospheric pressure between the Icelandic Low and the Azores High, has been shown to influence which of the two deep Slope Water types dominates in the Slope Sea source waters immediately offshore of the Northeast Channel (e.g., see Petrie, 2007). During years of Low NAO winter indices, the transport of the Labrador Current is intensified, bringing colder, relatively fresh Labrador Slope Water to the Slope Sea, while at the same time, the north wall of the Gulf Stream shifts southward, allowing more Labrador Slope Water to penetrate farther to the southwest, making LSW available to enter the Northeast Channel. During years of High NAO winter indices, the opposite holds, and more WSW is available to enter the Gulf.

In addition to the evidence cited above of NAO effects on the oceanography of the northwest Atlantic Ocean, Thomas et al. (2003) showed potential evidence of the NAO effects in hydrographic and nutrient profiles taken in the Northeast Channel in March of 1997, 1998 and 1999; those results are re-plotted here (Fig. 6). Evidence of a Labrador Slope Water mixture is identifiable on the bottom in the Northeast Channel in 1997 and 1999 as a cold water mass beneath a much thicker layer that is a mixture dominated by WSW, making that layer significantly warmer and slightly saltier than the bottom layer. That there is significant mixing between the two layers is evident in the slightly warmer bottom temperatures (>8 °C) than would be expected of Labrador Slope Water; water properties assumed by Mountain (2012) and others are 6 °C and 34.6 ‰ for LSW, and 12°C and 35.4 ‰ for WSW. In 1998, two years following an exceptionally low NAO winter index in 1996, LSW appears to be the dominant water mass throughout much of the deep and bottom water column, as discussed by Drinkwater et al. (1998). However, the cold water temperatures, below 5 °C at 200 m (Fig. 6) and relatively fresh salinities (≤ 34.2 ‰ at 200 m) reflect either much lower temperatures for LSW than those cited in the literature (e.g., see Mountain, 2012) or significant mixing of LSW with a colder and fresher water mass. We suggest that SSW may have an important role in the supply of water entering the Gulf through the Northeast Channel, potentially mixing with and modifying the properties of LSW, upstream of the Channel, possibly on the Continental Slope where Scotian Shelf Waters overly LSW (Gatien, 1976). This would explain the observed water properties in the Northeast Channel, shifting the LSW from its presumed initial values of 6 °C and 34.6 ‰. Evidence of this can be clearly seen in Figure 6. If this were the case then the nutrient loads of Slope Water inflows through the Northeast Channel would be reduced.

While, as just mentioned, the water properties at 200 and 250 m in Jordan Basin generally track one another closely over the 10 year data record, with temperatures, for example, plotting almost as one (with 200 m waters only slightly cooler than 250 m), there were periods when the salinities did not track as closely. Unlike most of the time series record, there are four episodes when the salinities at 200 m are significantly fresher than at 250 m: summer 2007, winter-summer 2008, spring 2012, and summer-fall 2012. The fresher waters at 200 m during those episodes can only have resulted from an influx and/or deep mixing of coastal/shelf waters, and not an influx of LSW, which, being the densest water mass, would be confined to the bottom layer, as shown for example in the station profiles in Figure 6.

The water properties at 100 and 150 m, in Figure 5, follow closely the general patterns seen at 200 and 250 m, but show a wider range of values, with temperatures varying by about 5 °C at 150 m over the 10-year record, and more than 6 °C at 100 m. The same pattern is seen for salinity, with the range in salinities greater at 100 m than at 150 m. The greater high frequency variability in water properties at these shallower depths is, we expect, primarily the result of internal tides and internal solitary waves. The general trends in water properties identified for depths of 200 and 250 m are reflected in these data for 100 and 150 m, with brief periods of cold and fresh waters in 2004-2005, a period of warmer and saltier conditions the following two years (in two peaks, in the winters of 2006 and 2007), followed by cooler and fresher waters between 2007 and late 2009, and a generally warmer, saltier period from late 2010 to the present. However, there are important differences: First, there is evidence of an annual cycle in these data, as water temperatures correspond with winter cooling and convective mixing, and summer warming, especially for the waters at 100 m, which are warmer than 150 m water in the late fall and early winter, and colder in late-winter to early-spring. The seasonal influx of Scotian Shelf Water in winter-spring, however, is not immediately evident in these salinity data from 100 and 150 m. Second, there are several episodes of extreme freshening of 100 m waters during spring: in 2004, 2005 and 2010. Corresponding late-winter, early-spring temperatures were colder in 2004 and 2005, and each spring from 2007 to 2010. Deese-Riordan (2009) hypothesized that the observed Gulf-wide freshening in 2004-2005 may have been due to fresher than normal Slope Water entering through the Northeast Channel, larger than normal volumes of freshwater inflow into the Gulf, or a greater volume inflow of SSW.

These data for Jordan Basin are coherent with trends in water properties at depths of 100, 150 and 180 m in the Northeast Channel (Fig. 7) at UMOOS Buoy "N" (Fig. 1), which show the same episodic patterns of cool, low salinity waters alternating with warmer, higher salinity waters. However, the degree of high frequency variability in temperature and salinity data from the Northeast Channel mooring is greater than in Jordan Basin, with variability increasing with decreasing depths. Short term variability at 100 m is on the order of 6 °C and 2 ‰, or about twice that seen at 100 m in Jordan Basin. These greater short term fluctuations in temperature and salinity in the Northeast Channel, compared to Jordan Basin, are likely the result of the Northeast Channel's closer proximity to the boundary water masses influencing the Gulf of Maine. The dynamics and variability of inflow through the eastern side of the Northeast Channel and the influence of variability in outflow through the western side of the Northeast Channel also increase variability at the buoy site. These, along with the influence of eddys and rings from the Gulf Stream, variability in the flow of SSW over the Northeast Channel, the magnifying effect of channel processes, proximity to the foot of the shelf-slope and the dynamics of the offshore water masses, all combine to increase observed variability at the Northeast Channel buoy site. Again, as already discussed, the fate of these waters sampled on the eastern side of the Northeast Channel cannot be stated with certainty, as they may circulate in Georges Basin and exit the Gulf via the western side of the Channel. Nonetheless, they are generally coherent, with a lag of 2 to 3 months, with the patterns observed in Jordan Basin (Deese-Riordan, 2009), with the notable exception that as those waters in the Northeast Channel flow to Jordan Basin, their water properties are further modified by mixing with shelf waters, as the temperatures in Jordan Basin at 100 and 150 m, for example, are colder and fresher than in the Northeast Channel at the same depths.

In both Figures 4 and 5, for Jordan Basin, there is evidence at all four depths, 100, 150, 200 and 250 m, of an increase in temperature and salinity during the summer to winter period of 2013-2014; that increase is especially rapid at depths of 100 and 150 m (Fig. 5). Typically the inflow of Slope Water into Jordan Basin at depths of 200m and 250m peaks in early fall, usually lagging by about 2-3 months the period of maximum inflow of Slope Water through the Northeast Channel. Variability in the volume and characteristics of this deep Slope Water supply dominate at 200 and 250 m over seasonal variability. Data from 100 m for that period are re-plotted in Figure 8, along with nitrate concentrations at 100 m as reported by the Satlantic ISUS nitrate sensor. A noticeable feature of those data is the dramatic short term (a few days) increase in temperature and salinity in July 2013, when the temperature increased by 2 degrees, from about 6.5 to 8.5 °C, and salinity increased by 0.5 ‰, from about 33.3 to 33.8 ‰, and was accompanied by a sharp drop in nitrate concentrations, from about 12 μM to less than 8 μM. Had we not possessed the nitrate data collected by the ISUS sensor, which in this case served as a semi-conservative water property, we would have incorrectly assumed that this event was an intrusion of WSW. That the nitrate dropped, and did not increase, as would have been the case with nutrient-rich WSW, we suggest that this event is an influx of Gulf Stream surface water. A similar but less pronounced event can perhaps be seen in late November-December.

The general trend revealed by these data in Figure 8 for the summer-to-winter period of 2013-2014, is an overall increase in temperature and salinity, indicative of an influx of WSW, with the salinities greater than 34 ‰ by November. This increase is not a result of convective mixing with deeper waters below 100 m, as can be seen in Figure 9, which plots sigma-t at each of the Jordan Basin sample depths (2, 20, 50, 100, 150, 200 and 250 m) over the same period. Wind and convective mixing are evident in the surface waters in September, and by November the water column has become vertically mixed to 50 m; but mixing does not reach 100 m until late December and early January, long after the salinities at 100 m reached 34 ‰ and the nitrate concentrations reached 17 μM (Fig. 8). After the ISUS nitrate sensor failed in mid December there were two episodes of decreased salinity at 100 m (Figures 8 and 9), with the second event lowering the salinity to less than 33.0 ‰. These events, apparently the result of an influx of Scotian Shelf Water, are clearly seen in the density structure in Figure 9, and are followed by a return to somewhat higher temperatures and salinities in February 2014.

The evolution of water properties in Jordan Basin from summer 2013 to winter 2014 can be seen most clearly in the T-S (temperature-salinity) diagrams in Figure 10, in which we present monthly subsamples from each depth (e.g., 2, 20, 50, 100, 150, 200 and 250 m). The summer T-S diagram (August) has the classical "V" shape that is typical of the offshore Gulf of Maine and illustrates the three prominent water layers in the Gulf (Hopkins and Garfield, 1979): 1) Gulf of Maine Bottom Water, made up of warm and salty Slope Waters; these deep and bottom waters include T-S pairs that fall on a line stretching to the upper right from the base of the "V"; 2) The base of the "V" is Intermediate Water, the coldest water in the Gulf (outside of winter), having been formed by convective sinking of surface waters the previous winter; 3) Surface Water comprises those T-S pairs to the left of the base of the "V", and includes the warmer, lower salinity, and least dense waters. Over time, the left arm of the "V" collapses, as heat is lost from the surface layers, but at the same time, we can see by October that the water properties at 50 and 100 m are being stretched, as they become not only warmer, but also saltier as indicated by the arrows in Figure 10. These intermediate depths are changing as WSW moves into the mooring location, causing a wave-like over-riding of 100 m water upward and to the right in the T-S diagram, as those waters become progressively warmer and saltier. The waters beneath, at 150 m and deeper, remain unaltered from October to December. By January, convective mixing has reached 100 m, and the presumed inflowing WSW begins to mix with the deeper waters. Also in January, cold and fresh SSW can be seen intruding into Jordan basin at depths from the surface to 50 m, and mixing to 100 m by February. This produces the extension of T-S data pairs to the lower left of the T-S diagrams for January and February (Fig. 10).

It is important to point out that this influx of WSW into Jordan Basin in the fall-to-winter period of 2013-2014 was well up off the bottom, mixing first with waters at 50 and 100 m (Fig. 10); the WSW was not a penetration of bottom water, at least not initially in the fall of 2013. Smith et al. (2012) clearly show inflowing Slope Waters (they did not distinguish between WSW and LSW) at all depths in the Northeast Channel, with the maximum flow well up off the bottom between about 30 and 100 m. This influx and mixing of WSW in the fall-winter of 2013-2014 combined with the earlier deep influx of WSW in July 2013, created one of the warmest and saltiest events at 200 and 250 m of the 10-year record shown in Figure 4, and is among the warmer and saltier events at 100 and 150 m (Figure 5).

4. Discussion.

The results presented here clearly demonstrate that variability in proportions of the three water masses that enter the Gulf of Maine – Scotian Shelf Water (SSW), Labrador Slope Water (LSW) and Warm Slope Water (WSW) – are important to the Gulf's bulk water properties, especially water temperatures. However, much of the literature has focused on the role of which of the two Slope Water types dominates in the Gulf of Maine and adjacent continental shelf waters, based on the supposition that episodes of enhanced or reduced fluxes of cold LSW versus the warmer WSW, under the influence of NAO, were the important drivers of historical temperature fluctuations, such as the "cold 1960s" (e.g., Drinkwater et al., 1998; Pershing et al., 2001; Green and Pershing, 2003; Drinkwater et al., 2003; Petrie, 2007; and Mountain, 2012). It is worth noting that Bigelow (1927) took great pains to argue that the previously-assumed role of waters of Labrador Sea origin as a "cooling agent" in the Gulf of Maine was based more on hypothetical grounds than on direct observation (p. 826). He argued that it is SSW that is the chief cooling agent (and source of much of the Gulf's fresh waters). While today Scotian Shelf Waters are recognized as important to surface salinities in the Gulf, much of the attention in the literature is focused more on its role in establishing vertical stratification for phytoplankton bloom phenomena (e.g., reviewed in Ji et al., 2007) than as a cooling agent. Consequently, the relative contributions of SSW to the Gulf's bulk water properties, both temperature and salinity, have received less attention, despite evidence of its inflows to the Gulf having become more variable, or having increased, in recent years (Smith et al., 2001; 2012; Pettigrew et al., 2008; Townsend et al., 2010). As can be plainly seen in Figures 4 and 5, deep and bottom water salinities in Jordan Basin commonly drop to below the normally cited values of 34.6‰, the characteristic salinity of LSW and, of course, well below 35.4‰, the normally cited values for the characteristic salinity of WSW (Gatien, 1976; Mountain, 2012). Bigelow (1927) showed that river inputs contribute less than half the freshwater flux to the Gulf, with the greatest freshening of surface waters observed in the western Gulf, and that SSW, which enters the eastern Gulf, was the major source.

The importance of Scotian Shelf Water to the water properties and nutrient content in the Gulf of Maine was illustrated in an analysis of historical data by Townsend et al. (2010). They described variations in deep (>100m) water properties (temperature and salinity) and concentrations of nitrate and silicate in the Gulf of Maine, which were not correlated with NAO. Their analyses showed that, when averaged by decade, the deeper waters in the Gulf (>100m) have changed since the 1970s, becoming slightly fresher and cooler, with lower nitrate (by ca. 2-4 µM) but higher silicate (also by ca. 2-4 µM), changes that were opposite to that expected based on cycles in the North Atlantic Oscillation. For example, as shown in Figure 11, the deep and bottom water concentrations of silicate and nitrate changed between 1985, when nitrate concentrations exceeded silicate, reflecting a deep Slope Water source, to virtually the same concentrations in 2006. Both Slope Water types, WSW and LSW, have 5-10 µM greater nitrate concentrations than silicate. This altered nutrient regime in the Gulf of Maine, as exemplified in the 2006 example in Figure 11, was interpreted as the result of a greater influence at depth of Scotian Shelf Waters, as compared with LSW and WSW. Townsend et al. (2010) suggested that increased freshwater discharges from Arctic rivers and melting of the Arctic ice cap since the 1970s (reviewed in Perovich and Richter-Menge, 2009) may have intensified the southward baroclinic transport of shelf and Slope Waters in the Labrador Sea and along the coasts of Maritime Canada and the Northeast U.S. (Greene et al., 2012). As those shelf and Slope Waters mix off Labrador and Newfoundland and flow along the continental shelf at all depths from the Grand Banks of Newfoundland to the Gulf of Maine, the nutrient loads likely become altered by both benthic denitrification, which depletes nitrate concentrations (e.g., Christensen et al., 1996), and accumulations of terrestrially-derived silicate in river run off (Townsend et al., 2010). More recent studies have shown that such altered nutrient fluxes may be forcing changes in the structure of the planktonic ecosystem, especially blooms of *Alexandrium fundyense*, the toxic dinoflagellate responsible for Paralytic Shellfish Poisoning (McGillicuddy et al., 2011; Townsend et al., 2014). McGillicuddy et al. (2011) showed that an episode of low-nitrate shelf water fluxes may have resulted in a muted spring phytoplankton bloom in the Gulf of Maine that year, and a significant reduction in *A. fundyense* populations throughout the Gulf and on Georges Bank. Most recently, in November 2013, we see proportions of nitrate and silicate concentrations in deep and bottom waters of Jordan Basin that are more like those in the 1980s and earlier, with significantly greater concentrations of nitrate than silicate, reflecting a greater influx and mixing of WSW relative to SSW (Fig. 11). Therefore, these periods of alternating differences in nitrate and silicate concentrations in the Gulf would suggest episodic differences among years in the proportions of SSW and the sum of the two Slope Waters, LSW and WSW.

The episodes of colder and fresher water properties, alternating with periods of warmer and saltier waters at deep and intermediate depths in Jordan Basin (Figs. 4 and 5) can be examined using T-S analyses and a 3-point mixing triangle, as described by Mountain (2012) and illustrated in Figure 12. While we use the cited T-S values for WSW and LSW here, it is important to point out that there is a range of values for LSW and WSW. To illustrate this we have included in Figure 12 T-S envelopes for WSW and LSW using the range of values given by

Petrie and Drinkwater (1993), after Gatien (1976). Analyses of average water properties during peak times of alternating episodes at 250 m in Jordan Basin, as identified in Figure 4, reveal that they are principally a function of the relative proportions of WSW and SSW and implies the influence of a fresher water mass in the bottom of Jordan Basin, that falls outside the envelope of the values described for LSW. Thus, the warm and salty episodes at 250 m are the result of proportionally greater volumes of WSW and less influence of SSW, while the colder and fresher episodes may have been the result of greater influence of SSW and less of WSW. Qualitatively, we can see that were we to extend the SSW point in the mixing triangle in Figure 12 from 2 °C to 4 °C, most of the data points at 100 m would be captured, as average T-S pairs for episodes at 100 m plot well to the left of corresponding values for 250 m. The cool and fresh events at 100 m, for example, reflect significant influence of SSW or Slope Water characteristics well outside the expected range.

In order to explain the water property variations in Figure 4, the temperature and salinity of LSW must have been exceptionally low or a fresher, cooler water mass, such as SSW, must comprise a portion of the water masses supplying Jordan Basin at 250 m. Evidence of this can also be seen in the Northeast Channel (Fig. 7) where salinities at 180 m are often lower than 34.6 ‰ (characteristic of LSW), especially between 2007 and 2009. At 150 m and 100 m in the Northeast Channel salinities are even fresher. Additionally, the temperatures observed at Buoy N are colder than the characteristic values of the presumed bottom source waters entering through the Northeast Channel.

Typically, interannual variations in water properties, especially water temperatures, in the Gulf of Maine have been attributed to the relative proportions of WSW and LSW, with the relative fluxes of each under the influence of the North Atlantic Oscillation (e.g., Drinkwater et al., 1998; Pershing et al., 2001; Green and Pershing, 2003; Drinkwater et al., 2003; Petrie, 2007; and Mountain, 2012). It has also been suggested that differences in the nutrient loads in these two Slope Waters may influence biological productivity (Thomas et al., 2003; Townsend et al., 2006; Townsend and Ellis, 2010). Our results suggest the influence of a colder fresher water mass on the bottom waters of Jordan Basin, potentially linked to SSW. It is important to determine whether the freshness and coolness of conditions observed in the interior of the Gulf of Maine are due to variability in the normal range of temperatures and salinities of LSW or due to mixing of LSW with SSW upstream of Jordan Basin. This analysis of nutrient levels in Jordan Basin indicates that SSW may have a more important role at depths of 100m and deeper than previously realized. If this were the case then it is perhaps not surprising that there was no obvious correlation between water properties and the NAO over the period 2004 to 2014. Prior to this, from the 1960s to the early 1990s, Townsend et al. (2010) showed a positive correlation between NAO and water temperatures below 100 m in the Gulf of Maine, but not after the mid 1990s. Mountain (2012) examined water properties in the Northeast Channel between depths of 150 and 200 m and found a significant correlation between NAO and the percentage of LSW, but that the correlation was weaker after the 1990s. Because Mountain (2010) examined only those waters in the Channel, and not in the interior Gulf of Maine (Jordan Basin), his results and ours are not directly comparable. However, the coherence between general trends in water mass properties in the Northeast Channel and Jordan Basin would indicate that, indeed, a significant fraction of the waters in Jordan Basin passed through the Northeast Channel and that the characteristics of the deep water masses of Jordan Basin are dominated by Slope Water inflow through the NEC.

5. Conclusions

We conclude that the lack of a relationship observed in recent years between the NAO and water properties in the interior Gulf of Maine or the Northeast Channel is a result of decreasing fluxes of LSW and greater fluxes of SSW, which have not only increased in recent years but exhibit unpredictable variations. The range of T-S values of bottom water observed in the Gulf and in the Northeast Channel are not easily explained by the major water masses normally considered in their makeup, if one assumes the conventional T-S values for LSW and WSW, and a broader range must be assumed, or a fresher and cooler Scotian Shelf Water mass must be part of the mixture. SSW, while being a fresher and lighter water mass typically confined to the upper 100 m of the Gulf of Maine, can nonetheless contribute to the bottom waters in the Gulf by way of mixing upstream, in the Gulf and on the Scotian Shelf. Similarly, LSW, present in the Emerald Basin on the Scotian Shelf (Petrie and Drnkwater, 1993) can modify the properties of that SSW, resulting in a denser shelf water mass that is capable of penetrating the bottom layers of the Gulf of Maine basins, while retaining a significant SSW characteristic. We further suggest that recent increases in SSW fluxes to the Gulf of Maine are coupled to freshwater discharges in the Arctic and their influence on baroclinic shelf currents, from Labrador to the Nova Scotian Shelf. The result is episodes lasting months to years of SSW or WSW-dominated water masses in the interior Gulf of Maine, thus affecting the Gulf's nutrient loads. Further and more detailed characterizations of the water masses flowing into the Gulf of Maine and their interactions – before they enter the Gulf, as they enter, and after they enter – are needed in order to fully understand the history and origin of water masses in the Gulf and how they are affected by upstream change, especially increased flow driven by upstream melt waters. The history and variability of these water masses are of great importance to the nutrient regime in the Gulf of Maine. Finally, we suggest that earlier studies of ecosystem function in the Gulf of Maine and adjacent waters in relation to variations in temperature and advection of zooplankton populations resulting from variable proportions of LSW and WSW (e.g., Greene and Pershing, 2000; 2003; Pershing et al., 2001; Drinkwater et al., 2003; Mountain, 2012) may be more the result of variable SSW fluxes.

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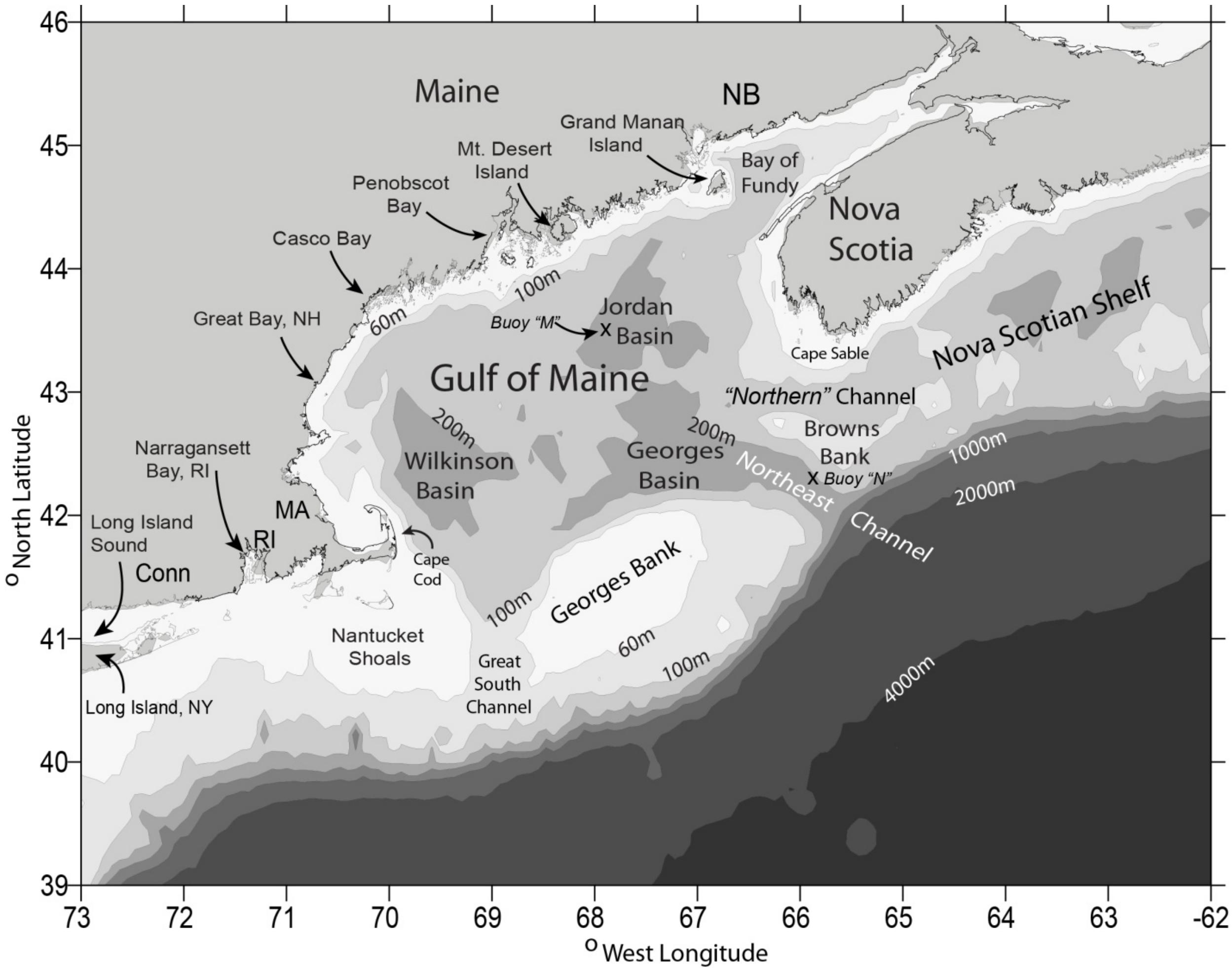

Figure 1. Map of the Gulf of Maine region showing main features of the bathymetry and the more important features referred to in the text. The location of Buoy "M" in Jordan Basin is given (x). The "*Northern*" Channel, depicting the channel between Browns Bank and Cape Sable, Nova Scotia, is the term used by Bigelow (1927).

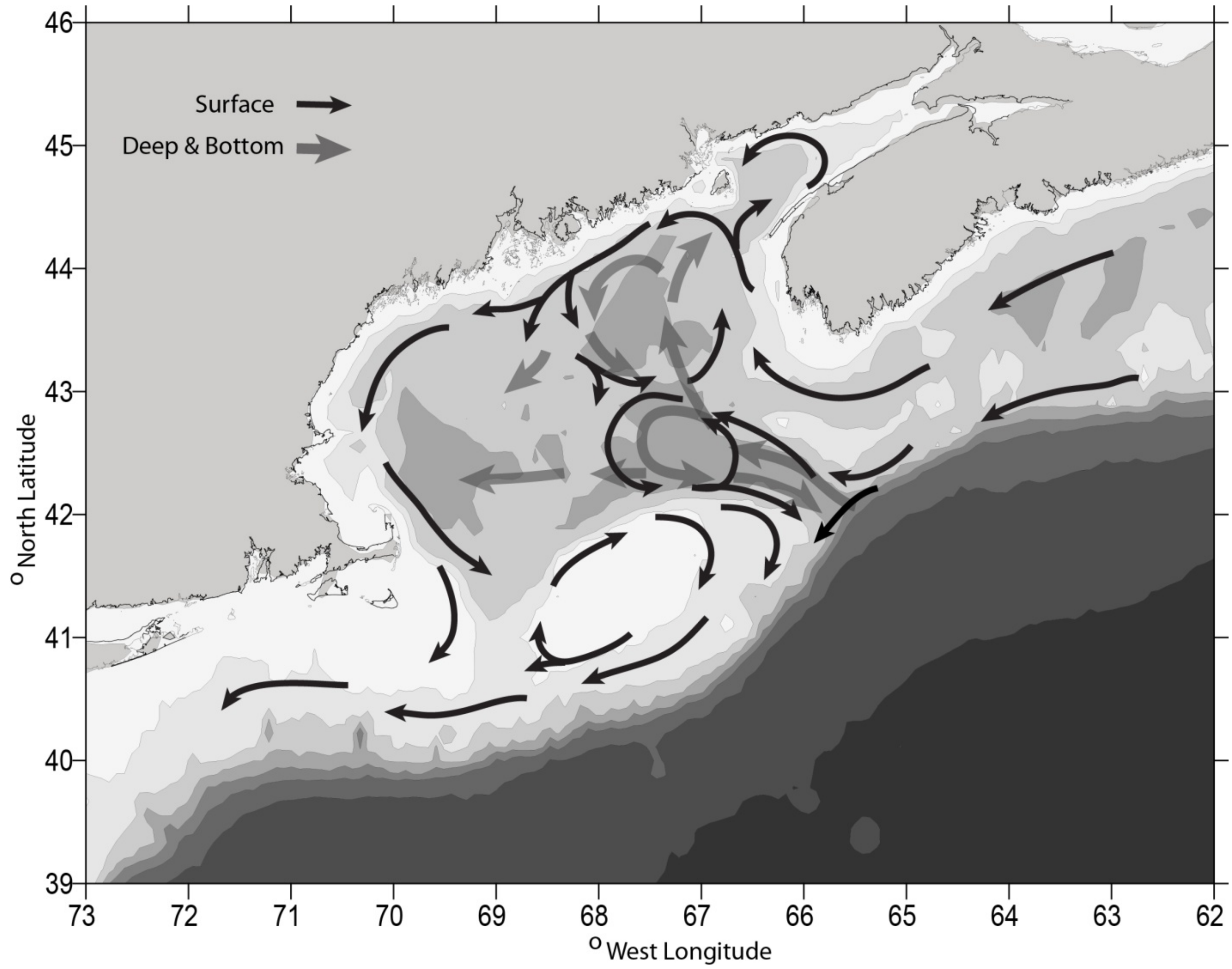

Figure 2. Schematic representation of the main features of surface currents in the upper 75 m, and deep and bottom currents, below 75 m in the Gulf of Maine region (after Brooks, 1985; and Beardsley et al., 1997).

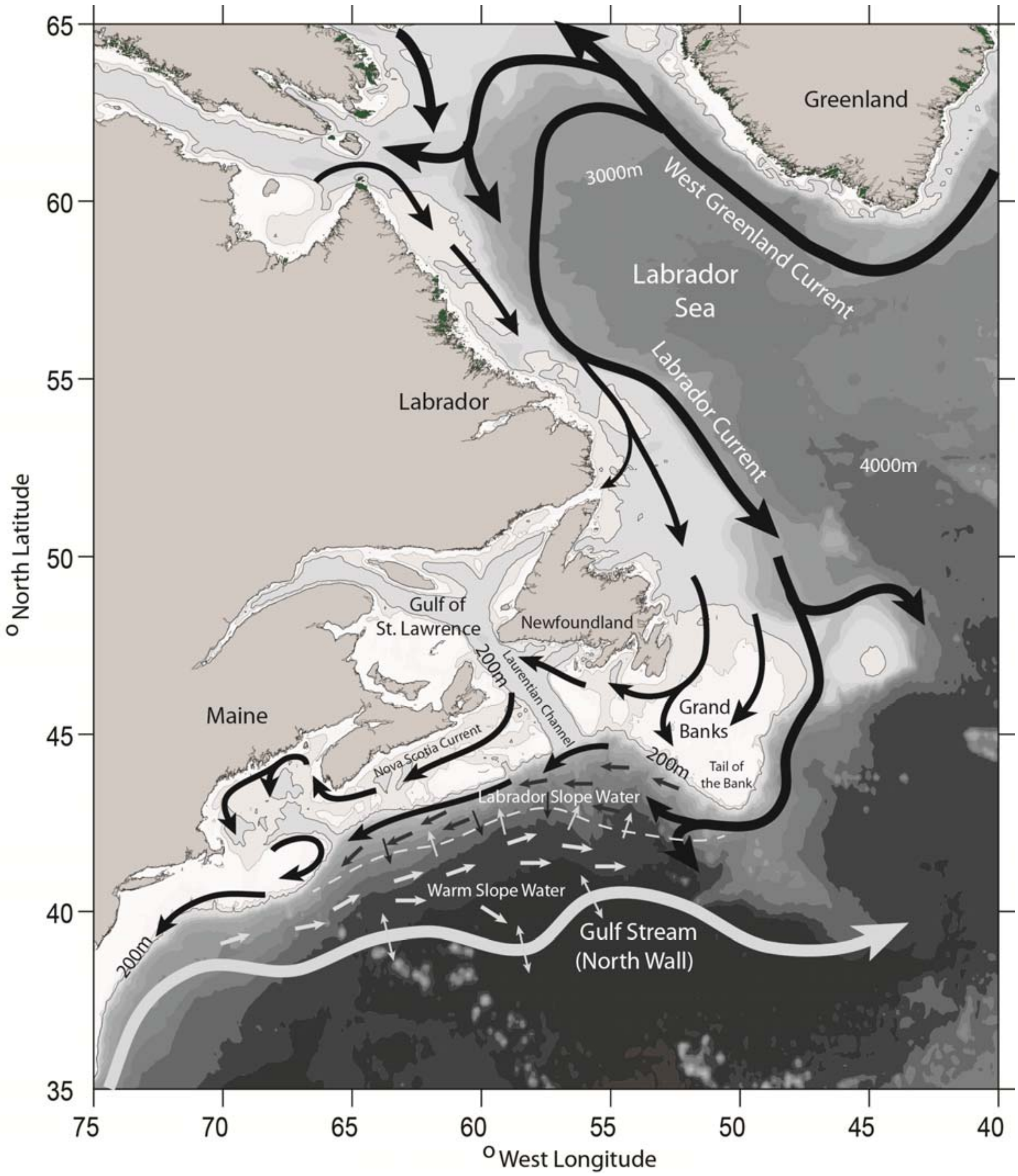

Figure 3. Bathymetric map of the NW Atlantic, indicating the position of the North Wall of the Gulf Stream, and major features of the Labrador Current with its offshore, slope component and continental shelf component, which crosses the Grand Banks and the Laurentian Channel, joining the Nova Scotia Current (after Chapman and Beardsley, 1989). The subsurface (~200 m) distributions of the two types of Slope Water, Warm Slope Water and Labrador Slope Water are shown schematically, separated by the dashed line, along with their presumed residual flows (short arrows); mixing of the water masses is also indicated by short arrows (after Gatien, 1976).

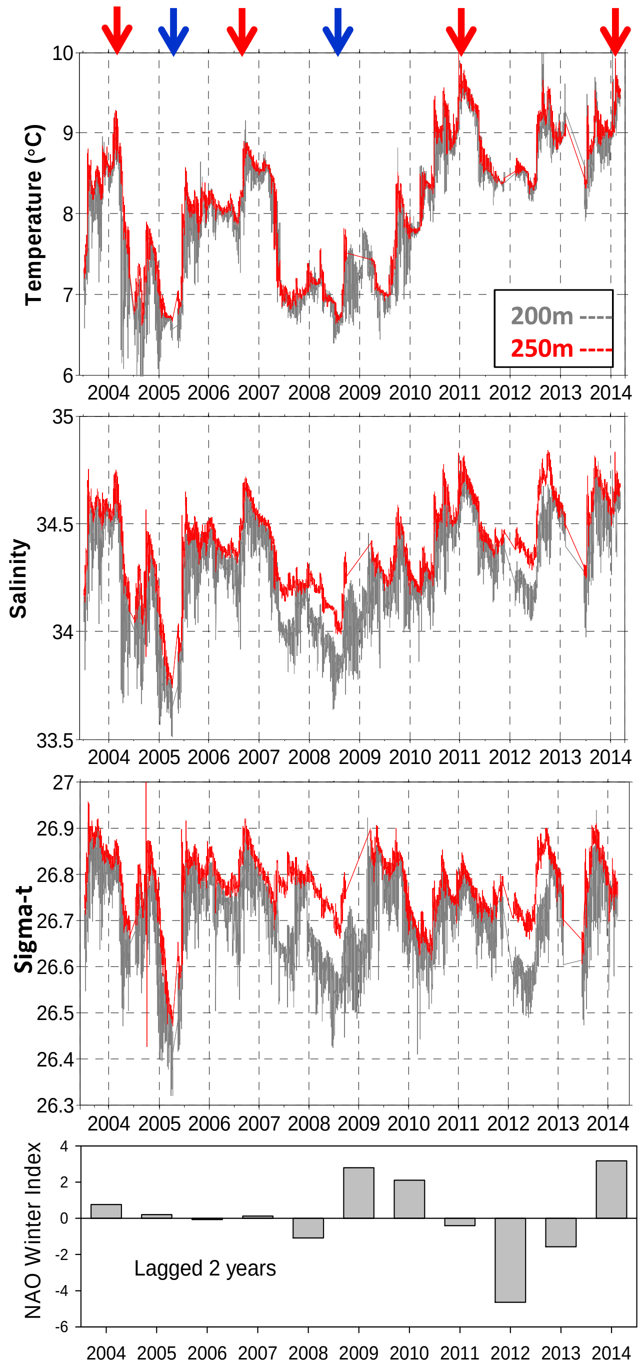

Figure 4. Temperature, salinity and density anomaly (sigma-t) at 200 and 250 m in Jordan Basin at Buoy M, of the University of Maine Ocean Observing System (UMOOS) for the period 9 July 2003 to 10 March 2014. The vertical dashed lines and year labels indicate January 1 for that year. Data were collected hourly, except for data gaps shown. Red and Blue arrows indicate warm and salty episodes and cold and fresh episodes discussed in text and analyzed in Figure 12. Bottom panel is the North Atlantic Winter Index, for Dec-Mar, for each year 2002 to 2012 (from The National Center for Atmospheric Research), plotted as the years 2004 to 2014 to reflect a two year lag (see text).

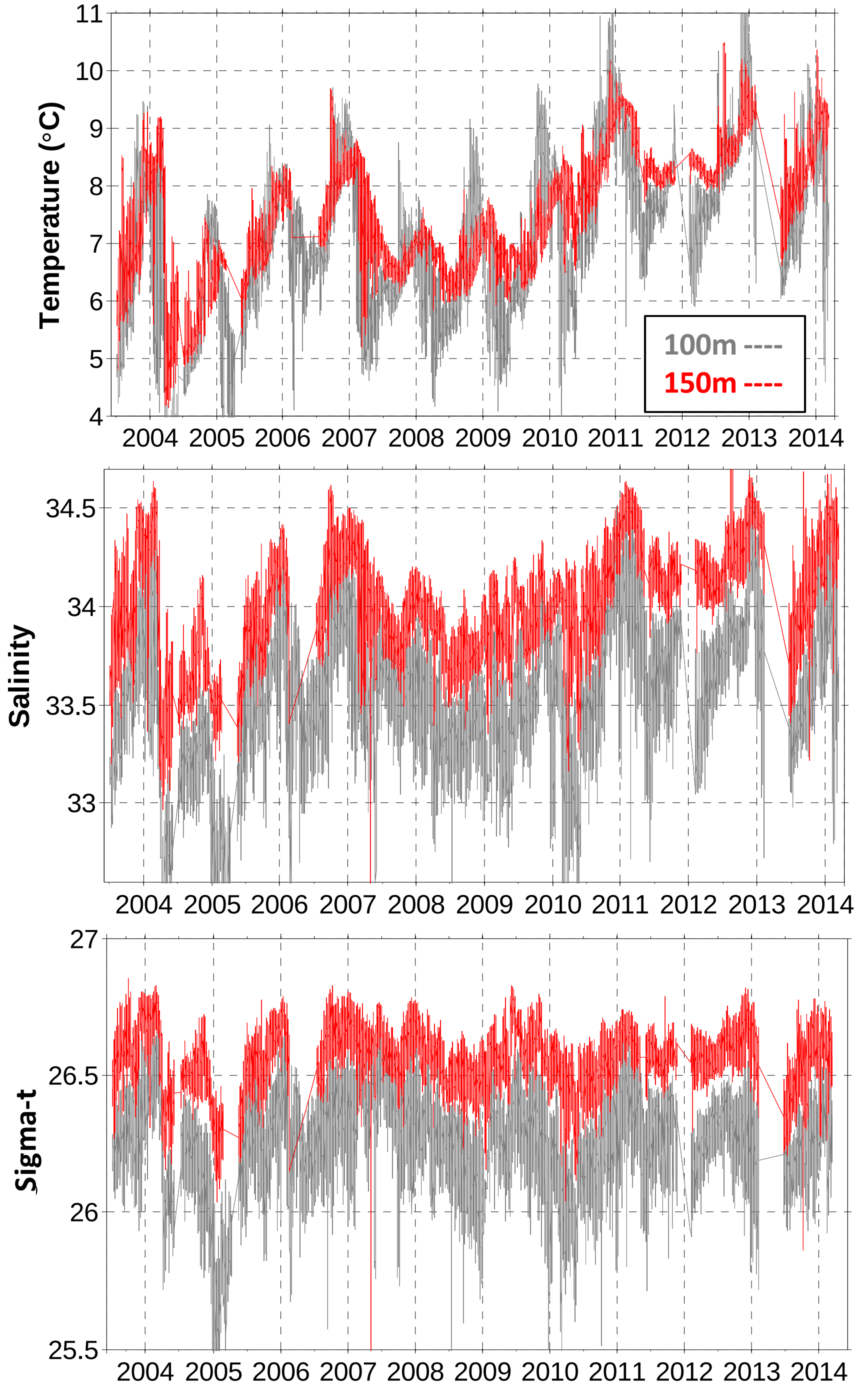

Figure 5. Temperature, salinity and density anomaly (sigma-t) at 100 and 150 m in Jordan Basin at Buoy M, of the University of Maine Ocean Observing System (UMOOS) for the period 9 July 2003 to 10 March 2014. The vertical dashed lines and year labels indicate January 1 for that year. Data were collected hourly, except for data gaps shown.

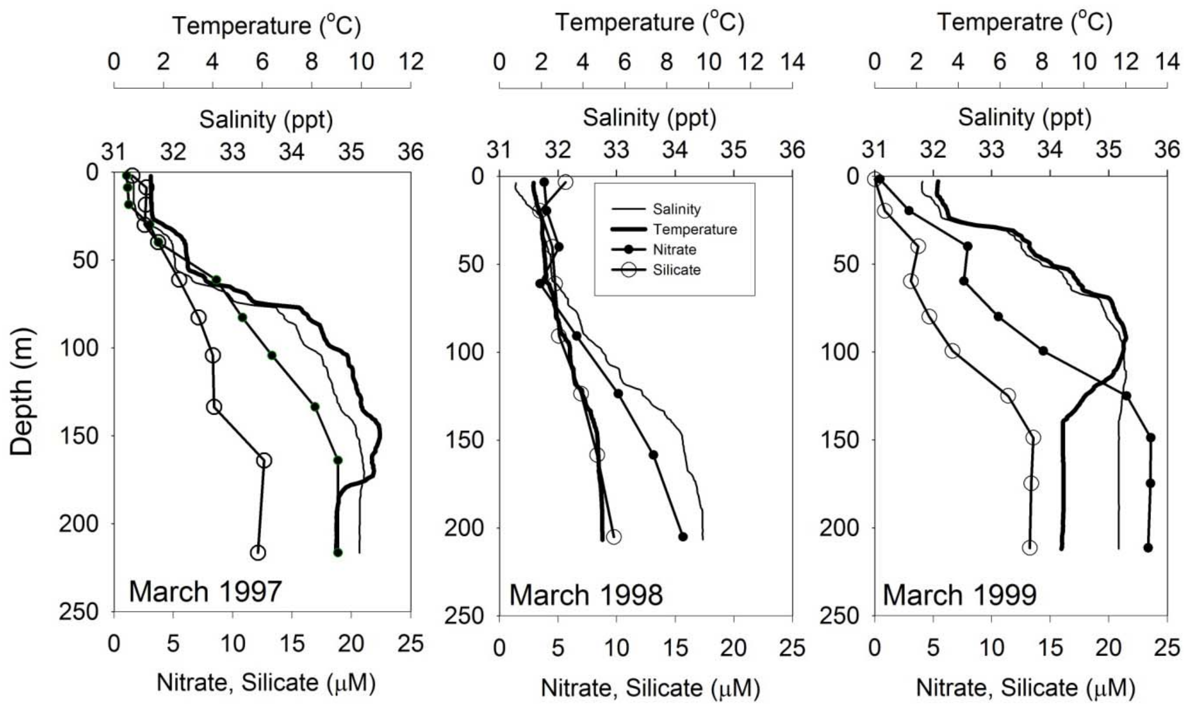

Figure 6. Profiles of temperature, salinity, nitrate and silicate sampled at a station in the Northeast Channel in March of 1997, 1998 and 1999; replotted after Thomas et al. (2003).

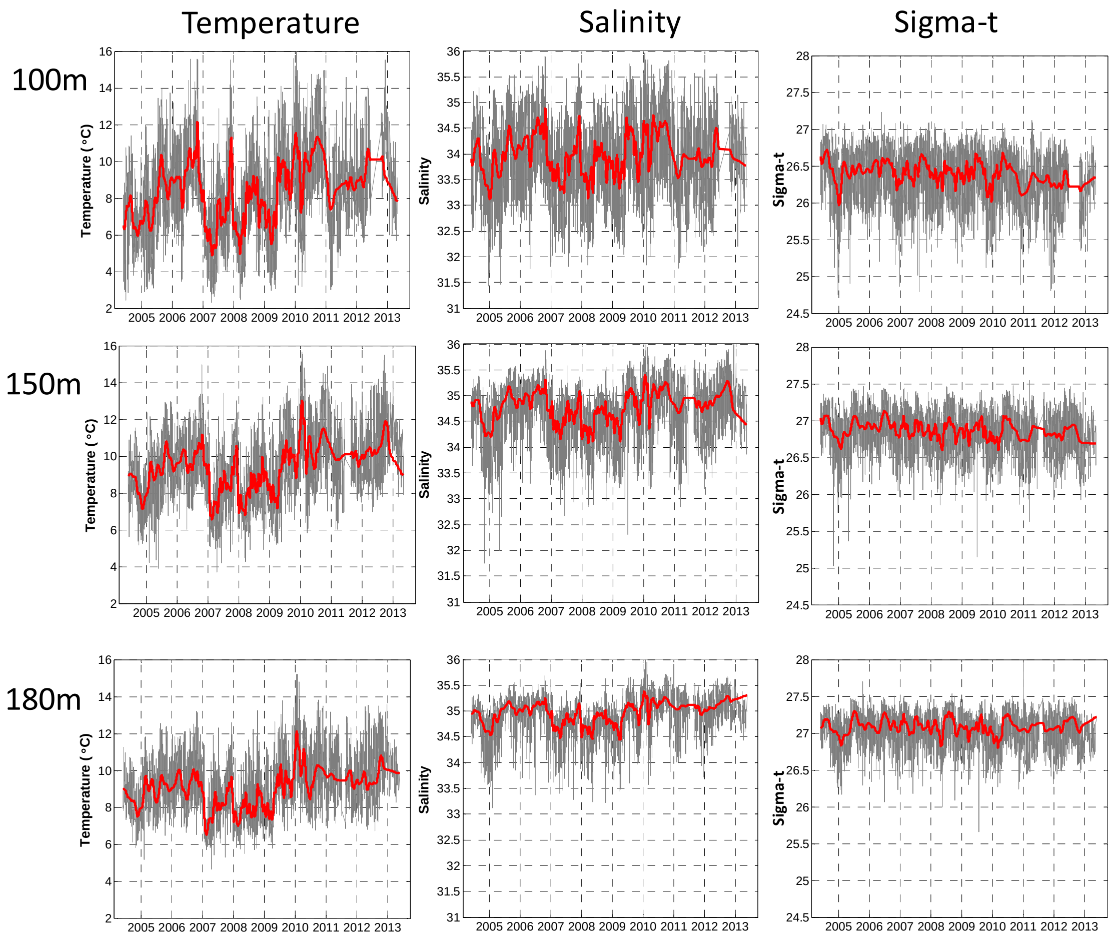

Figure 7. Temperature, salinity and density anomaly (sigma-t) at 100, 150 and 180 m in the Northeast Channel at Buoy N of the University of Maine Ocean Observing System (UMOOS) for the period 3 June 2004 to 7 May 2013. The vertical dashed lines and year labels indicate January 1 for that year. Data were collected hourly, except for data gapes shown. The heavy line is the 30-day running average.

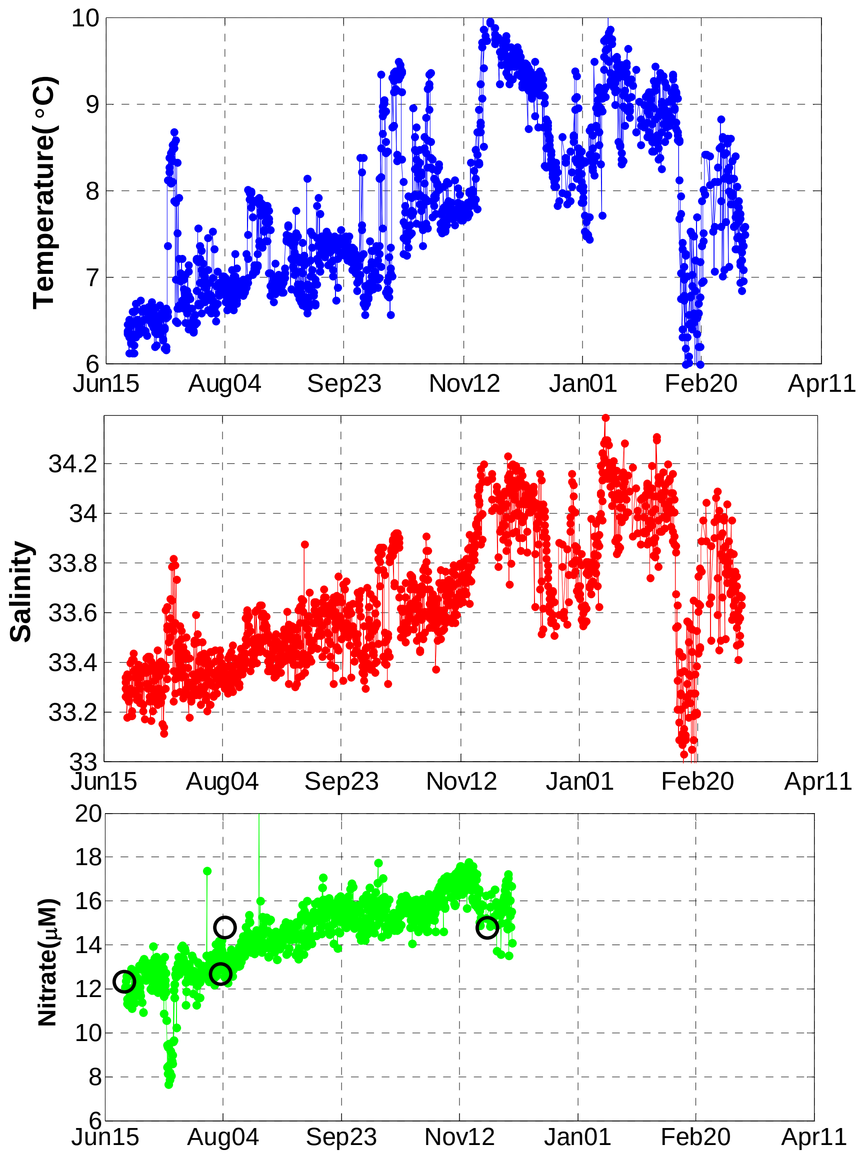

Figure 8. Temperature, salinity and nitrate data collected at 100 m at Buoy M, in Jordan basin, Gulf of Maine, from the time of deployment, 23 June 2013, to 10 March 2014. Nitrate data were collected 6 times per day; temperature and salinity data, recorded hourly, were subsampled to match the nitrate data. The ISUS nitrate sensor failed in December, 2013. Ground-truth water samples for nitrate analyses were collected at 100 m in Jordan Basin at the time of deployment (June 23, 2013; NO_3 = 12.24 µM) and again on two other occasions: Aug. 4, within 3 n. mi. of the site; NO_3 = 14.98 and12.62 µM; and Nov. 23, 2013, beside the mooring; NO_3 = 14.43 µM. These are plotted as open black circles (○).

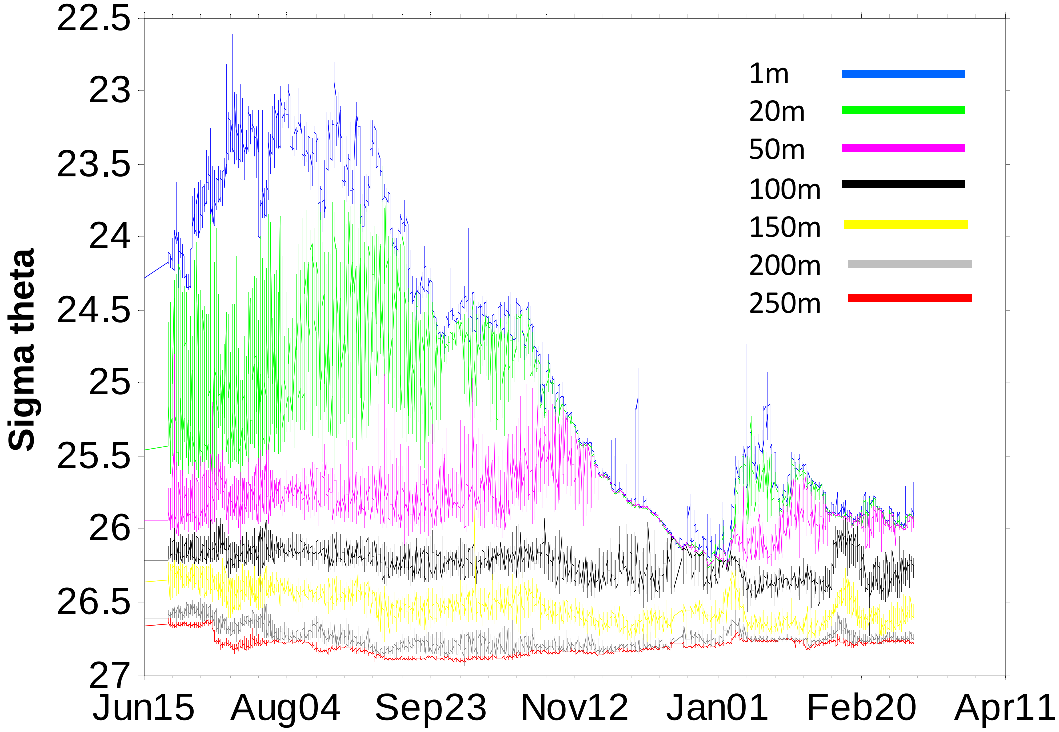

Figure 9. Density anomaly (sigma-t) at 1, 20, 50, 100, 150, 200 and 250 m in Jordan Basin at Buoy M, of the University of Maine Ocean Observing System (UMOOS) for the period 23 June 2013 to 10 March 2014. Data were collected hourly.

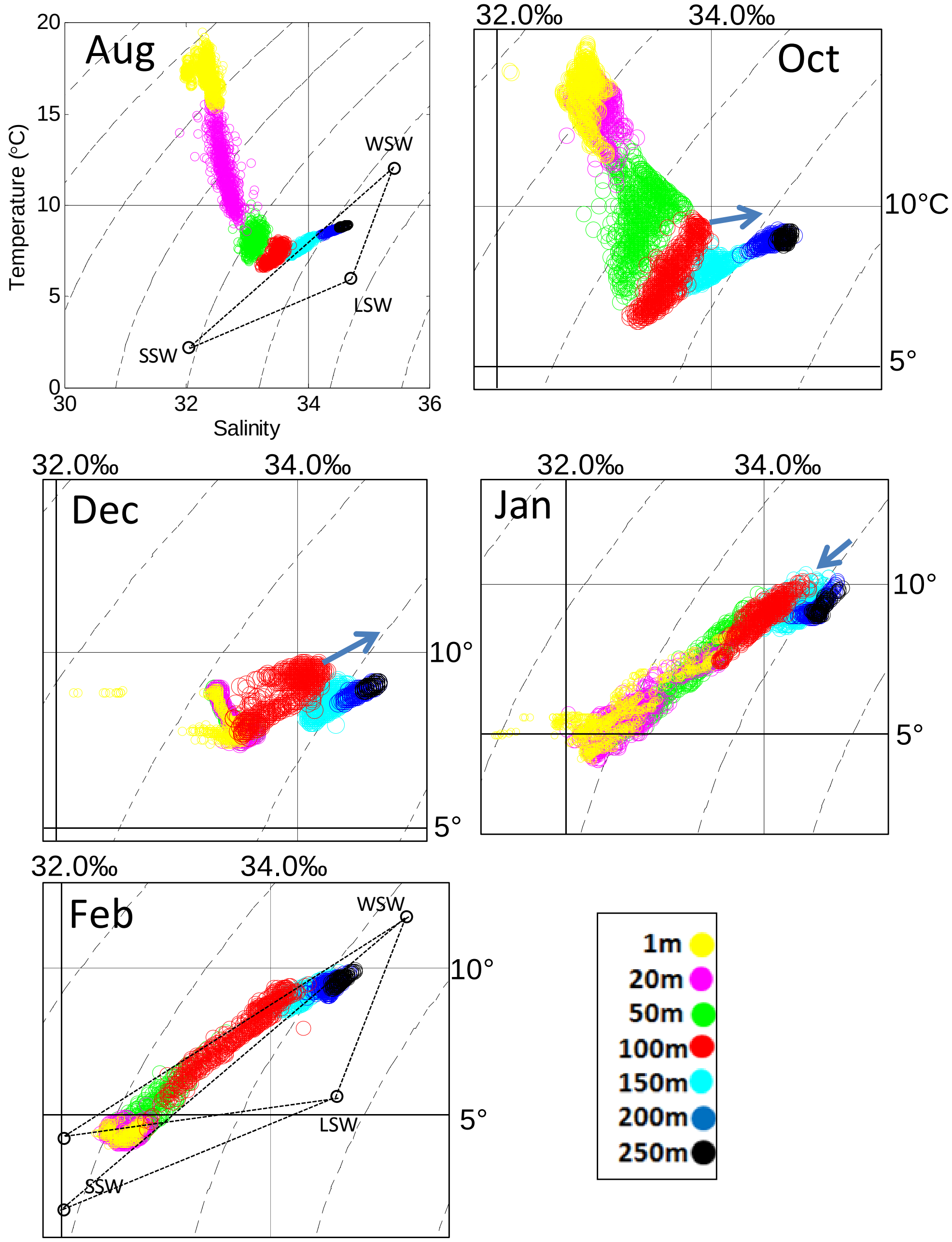

Figure 10. Temperature-Salinity (T-S) diagrams for data collected at 1, 20, 50, 100, 150, 200 and 250 m (color-coded) in Jordan Basin at Buoy M, of the University of Maine Ocean Observing System (UMOOS) for the months indicated in 2013 and 2014. The full T-S plot is given for August, 2013; the characteristic T and S for the three water masses, SSW, WSW and LSW are plotted, connected with a dashed line, indicating the three-point mixing triangle discussed in text. Close-up views are given for October, December, January and February. Lines at 10 °C and 34 ‰ are given in each panel; the blue arrows indicate the movement of the 100 m T-S data pairs betw een that month the following month. The February panel has the three-point mixing triangle as for August, but with a second overlapping triangle based on a temperature of 4 °C for SSW rather than 2 °C.

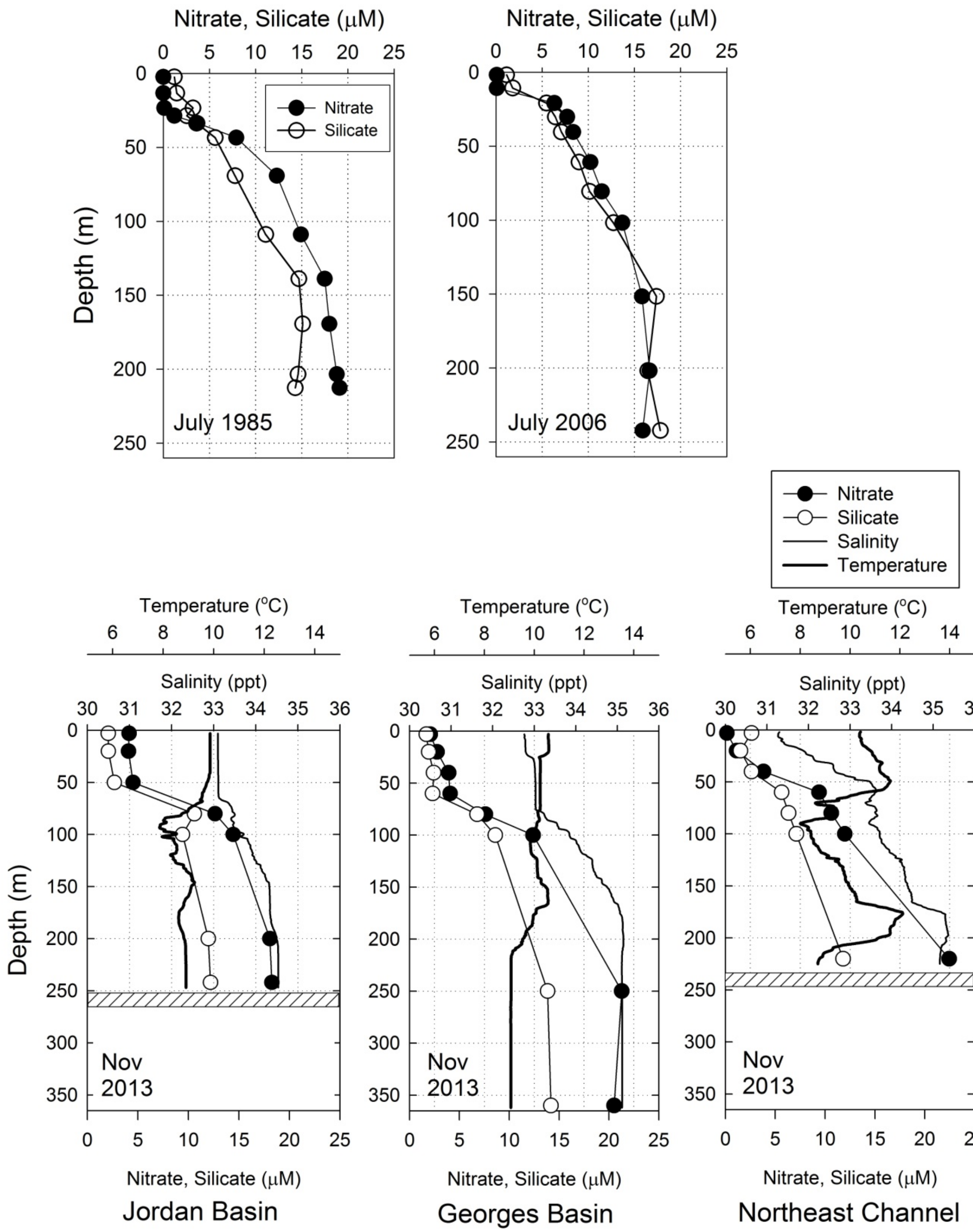

Figure 11. Top panels: Concentrations of nitrate and silicate at a station in Jordan Basin, in July 1985 and July 2006 (after Townsend et al., 2010). Bottom Panels: Temperature, salinity, nitrate and silicate profiles at stations in Jordan Basin, Georges Basin, and the Northeast Channel, in November 2013.

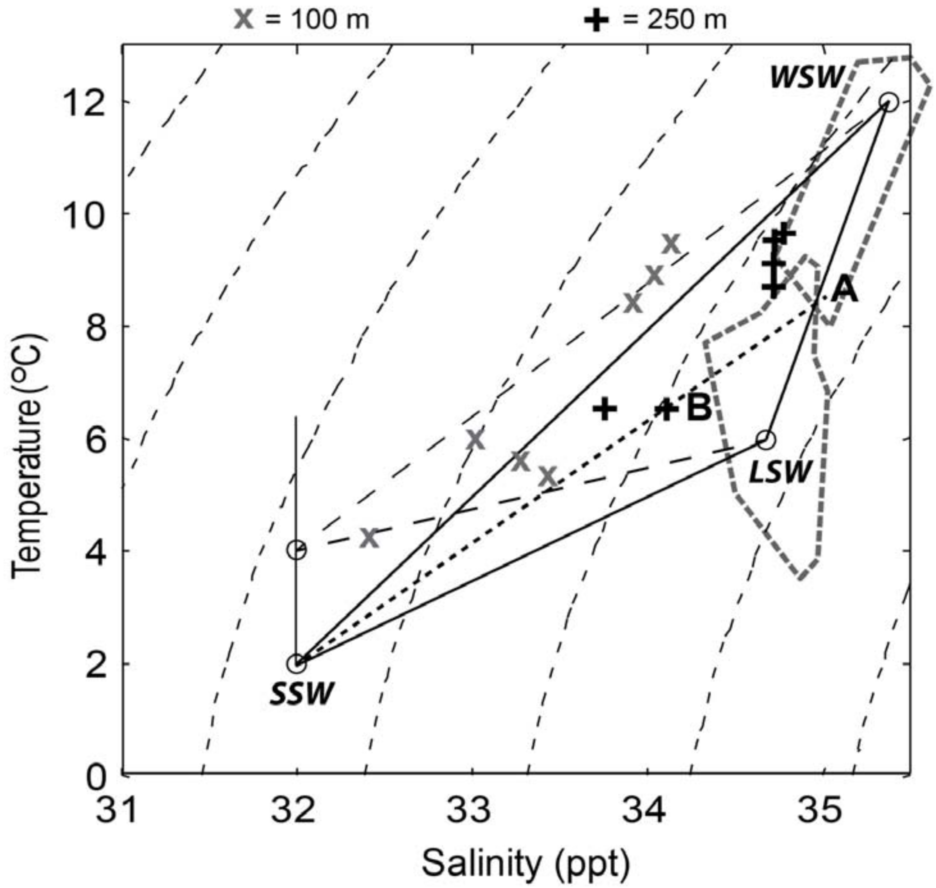

Figure 12. A T-S diagram upon which are plotted the T-S properties of the three water masses, WSW, LSW and SSW, connected to one another by a solid line forming a mixing triangle. The characteristic water properties of the three water masses (Mountain, 2012, and references therein) are: 6 °C and 34.6 ‰ for LSW; 12 °C and 35.4 ‰ for WSW, and 2°C and 32.0 ‰ for SSW. It is assumed that the waters in Jordan Basin are made up of these three water masses, and will plot within that triangle. A second mixing triangle with the same values for WSW and LSW but with a value for SSW of 4 °C and 32.0 ‰ is given, connected to one another with a dashed line; this second plot assumes a warmer SSW source water, or Gulf of Maine surface water, or a mixture of the two, of 4 °C. Also plotted are T-S envelopes (heavy dashed lines) for WSW and LSW using the range of values given by Petrie and Drinkwater (1993), after Gatien (1976). Average values of T and S for each of the episodes identified in Figure 4 (warm & salty and cold & fresh) for waters at 250 m in Jordan Basin are plotted (+), as are the T-S values for episodes at 100 m (x) in Figure 5, as discussed in the text. Proportional volumes of each water mass can be estimated as follows: The dotted line passing from SSW through Point B (+), for example, intersects the mixing line connecting WSW and LSW at Point A; the relative position of Point A on that mixing line gives the percent volume of each Slope Water type (WSW and LSW) of the total Slope Water volume. Likewise, the percent volumes of SSW and total Slope Water are determined by the position of Point B on the line between SSW and Point A on the Slope Water mixing line. All but two of the seven 100-meter T-S data lie outside the solid-line mixing triangle and inside the modified mixing triangle (discussed in text).