Journal of Marine Research, 73, 93–122, 2015

Water masses and nutrient sources to the Gulf of Maine

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ABSTRACT

The Gulf of Maine, a semienclosed 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 (SSW) from the Nova Scotian shelf that enters the gulf at the surface and slope water that enters at depth and along the bottom through the Northeast Channel. There are two distinct types of slope water, Labrador Slope Water (LSW) and Warm Slope Water (WSW); 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 to the Gulf of Maine is variable, that it covaries with the magnitude of inflowing SSW, and that periods of greater inflows of SSW have become more frequent in recent years, accompanied by reduced slope water inflows. We present here analyses of a 10-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 SSW and slope water inflows. We show that proportional inflows of nutrient-rich slope waters and nutrient-poor SSWs alternate episodically with one another on timescales of months to several years, creating a variable nutrient field on which the biological productivities of the Gulf of Maine and Georges Bank depend. Unlike decades past, more recent inflows of slope waters of either type do not appear to be correlated with the North Atlantic Oscillation (NAO), which had been shown earlier to influence the relative proportions of the two types of slope waters that enter the gulf, WSW and LSW. We suggest that of greater importance than the NAO in recent years are recent increases in freshwater fluxes to the Labrador Sea, which may 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 influxes of colder, fresher, less dense, and low-nutrient SSW into the Gulf of Maine and concomitant reductions in the inflow of deep, nutrient-rich slope waters. We also discuss evidence that modified Gulf Stream ring water may have penetrated to Jordan Basin in the summer of 2013.

Keywords. Gulf of Maine, water masses, nutrients, Labrador Slope Water, Warm Slope Water, Scotian Shelf Water, moored sensors, North Atlantic Oscillation

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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); however, 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. We now know that such is also the case in the Gulf of Maine, which receives waters from outside the gulf both at the surface and at depth (Bigelow 1927), with the deep slope water flows carrying the bulk of nutrients that drive 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). However, 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; Townsend et al. 2010; Pettigrew, Fikes, and Beard 2011; 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 partially 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 (Fig. 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 through the shallower "Northern Channel" between Browns Bank and Cape Sable (depth ~150 m; Fig. 1) such that the Gulf of Maine receives waters both at the surface and at depth in a flow-through fashion. Scotian Shelf Waters (SSWs) 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 SSW 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, Schlitz, and Wright 1985; Smith et al. 2001); this slope water layer is commonly defined by salinities greater than 34.0 per mille and, once inside the gulf, may extend upward from the bottom to depths less than

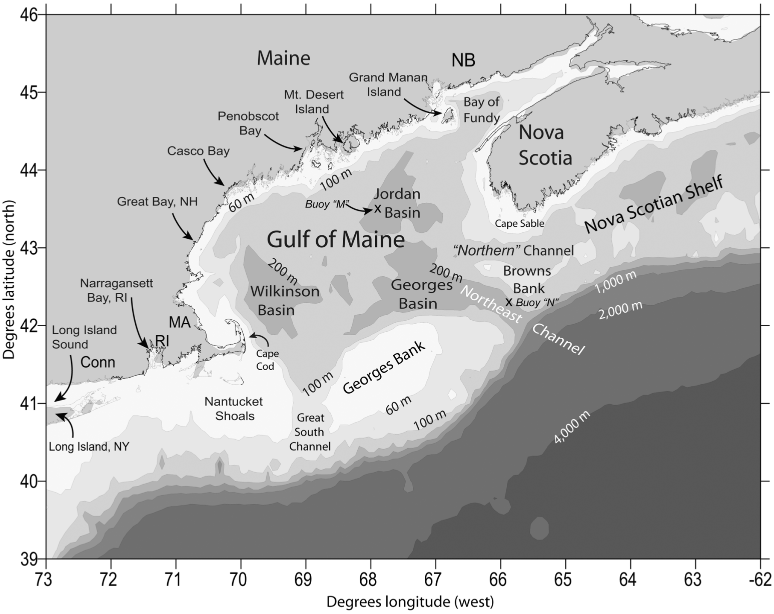

Figure 1. Map of the Gulf of Maine region showing main features of the bathymetry and the more important features referred to in the text. The locations of Buoy "M" in Jordan Basin and Buoy "N" are given (X). The "*Northern*" Channel, depicting the channel between Browns Bank and Cape Sable, Nova Scotia,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

75 m (Bigelow 1927). Additional inflow to the gulf occurs as a surface layer of cold and relatively fresh SSW 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 resides seasonally an intermediate water layer: convective sinking and mixing of surface waters in winter produces relatively cold water temperatures at depths between approximately 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 counterclockwise, gyre system of currents around the gulf, with cyclonic subgyres 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

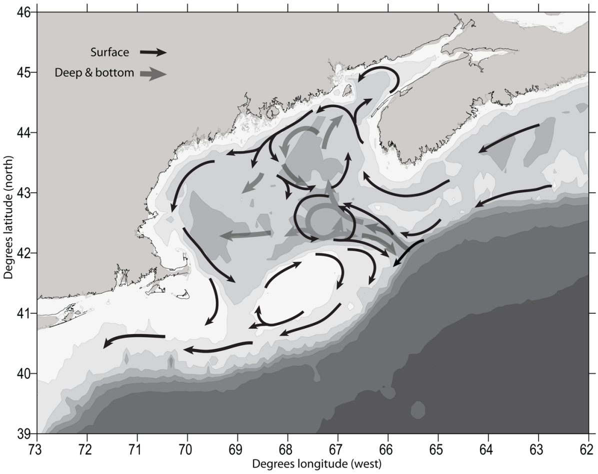

Figure 2. Schematic representation of the main features of surface currents in the upper 75 m and deep and bottom currents below 75 m in the Gulf of Maine region (after Brooks 1985; Pettigrew and Hetland 1995; and Beardsley et al. 1997).

Penobscot Bay and extending to coastal waters of Massachusetts), which flow east to west and are augmented by freshwater discharges from rivers. Details of these coastal currents are given in Lynch, Holboke, and Naimie (1997) and Pettigrew et al. (2005). The circulation on Georges Bank is anticyclonic (clockwise) and is driven by both density gradients and topographic rectification of tidal currents (Loder 1980; Lynch and Namie 1993; Xue, Chai, and Pettigrew 2000).

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 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 1997; Townsend et al. 2006; Hu et al. 2008; Townsend and Ellis 2010; Rebuck 2011). Once in the gulf, those deep nutrient-rich waters are brought to the surface by a number of physical processes, including vertical mixing by tides and long gravity waves, Ekman upwelling, 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, Townsend, and Weatherbee 2003; Rebuck 2011; Rebuck and Townsend 2014). Vertical mixing by tides occurs throughout the year and mixes deep water nutrients into 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

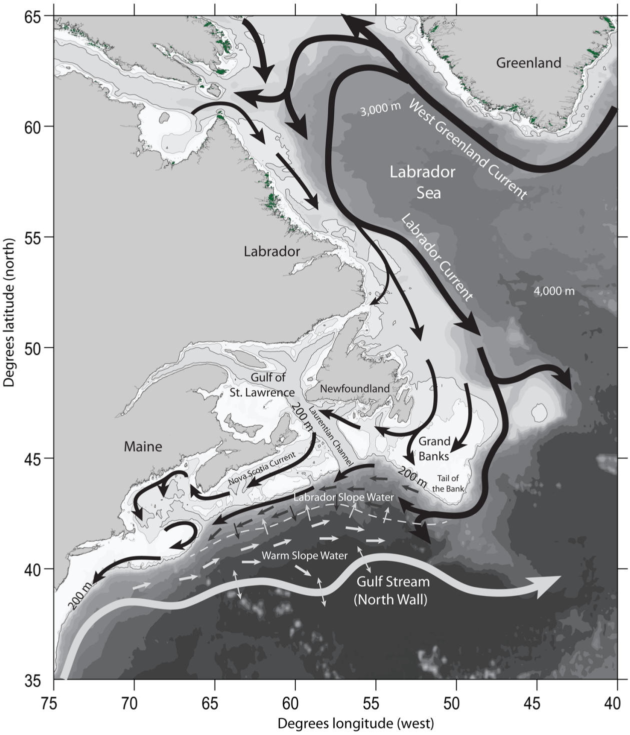

Figure 3. Bathymetric map of the northwest Atlantic, indicating the position of the North Wall of the Gulf Stream and major features of the Labrador Current with its offshore, slope component and continental shelf component, which crosses the Grand Banks and the Laurentian Channel, joining the Nova Scotia Current (after Chapman and Beardsley 1989). Warmer currents are colored gray, and colder currents black. 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).

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, Lauzier, and Bailey 1953), but Gatien (1976) showed that it is made up of two components: Warm Slope Water (WSW) and Labrador Slope Water (LSW). 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 it flows in a generally northeast direction adjacent to the Gulf Stream (Fig. 3). In addition to its warm temperatures and high salinities (Gatien 1976), WSW is characterized by its high nutrient concentrations below the surface (e.g., Townsend and Ellis 2010), which are from deep NACW. LSW is a deeper water mass that generally 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 than WSW (Gatien 1976) and significantly lower nutrient concentrations (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, Mountain, and Herman 1998, cited in Mountain 2012).

Decadal-scale hydrographic "regime shifts" in the Nova Scotian Shelf and Gulf of Maine region over the last century were described by Loder et al. (2001), in which changes in the shelf currents produced extended periods of anomalously cool and fresh conditions, particularly in the 1930s and 1940s, and again in the 1950s and 1960s. Changes in the inflows to the Gulf of Maine of deep slope waters through the Northeast Channel have been documented by Smith et al. (2001, 2012), Pettigrew et al. (2008), and Pettigrew, Fikes, and Beard (2011) based on moored current meter records. Historically, these deep water flows through the Northeast Channel have been assumed to be directed into the gulf at all depths on the eastern side of the channel and out of the gulf at shallow and intermediate depths on the western side, but with an overall net positive flow into the gulf, thus supplying the gulf with high-salinity, nutrient-rich waters. However, Smith et al. (2001) showed that inflows of slope waters were reduced during periods of enhanced inflows of SSWs at the surface in the Northeast Channel area and in the "Northern Channel" between Cape Sable, Nova Scotia, and Browns Bank. They showed that the SSW inflow during the period 1995–1996 increased by a factor of two, whereas the inflowing slope water was reduced by approximately half. Pettigrew et al. (2008), Pettigrew, Fikes, and Beard (2011), and Smith et al. (2012) showed that the flow pattern in recent years, beginning sometime after 2000, is characterized by episodes of greater outflow of deep waters through the Northeast Channel, hypothesized to be a mass balance response to a greater volume transport of shelf water from the Nova Scotian Shelf into the Gulf of Maine. Influxes to the gulf of fresher (and lower-nutrient) SSW create a barotropic pressure gradient that limits deep flows into the gulf of high-nutrient deep and bottom waters. Although the inflow of SSW to the gulf generally peaks in the winter–spring (Bigelow 1927; Smith 1983, 1989), Smith et al. (2012) showed that these mass fluxes are nonetheless episodic and are consistent with sea surface height anomalies off Nova Scotia as revealed by satellite altimetry data from 1992 to 2008. The last 15 years of that record show a contrast in sea level between the slope and offshore, indicating an accelerated westward flow and thus an increased mass flux from farther upstream (Smith et al. 2012).

Of particular importance to the biological oceanography of the Gulf of Maine region is the impact of altered slope water inflows on the delivery of nutrients to the gulf and Georges Bank, which happens in two ways. First, periods of reduced slope water inflows and concomitant greater SSW inflows will result in an overall reduction in the total nutrient flux to the gulf. Second, alternating proportions of the two slope water types that enter the gulf (LSW vs. 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 vs. 16–17 μM in LSW source waters), and silicate concentrations range from 10 to 14 μM, with WSW higher by approximately 10% (Townsend et al. 2006; Townsend and Ellis 2010). In both slope waters, nitrate concentrations exceed silicate by 5–10 μM. Of course, these nutrient concentrations become significantly diluted as the source waters are modified upon entry into and transit throughout the gulf. 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 and on Georges Bank, which receives its nutrient fluxes from the interior Gulf of Maine (Townsend and Pettigrew 1997; Hu et al. 2008).

We report here an analysis of 10 years' worth of moored buoy data from the University of Maine Ocean Observing System (UMOOS) along with recent and historical hydrographic and nutrient data. The combined data sets illustrate more clearly the nature of the three water masses—SSW, WSW, and LSW—of which inflows to the Gulf of Maine vary in an episodic fashion, thus creating variable water properties and dissolved inorganic nutrient loads. Our analyses reveal that in recent decades SSW has been assuming a more significant role in setting the hydrographic characteristics of the interior gulf, which in turn hold important implications for ecosystem dynamics in the region.

2. Data and observations

Results reported here are based primarily on mooring (buoy) data collected by the UMOOS, which is a component of the Northeast Regional Association of Coastal and Ocean Observing Systems (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 in real time and are available online (http://www.umoos.org/buoyhome.php). Also reported here are 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 (42°19.54′ N, 65°54.68′ W); bottom depth at the mooring site is 225 m. Details of the UMOOS are given in Pettigrew, Fikes, and Beard (2011). Additional archived hydrographic and nutrient data are also referenced (http://grampus.umeoce.maine.edu/nutrients/; Rebuck 2011), as are hydrographic profiles at stations sampled in the Gulf of Maine by a National Oceanic and Atmospheric Administration (NOAA) survey cruise in November 2013.

The Gulf of Maine offshore data buoys 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 in situ ultraviolet spectrometer (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 every 4 hours, which were averaged, giving six nitrate measurements per day.

The Jordan Basin mooring site was chosen to attach the ISUS optical nitrate sensor 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 sufficiently shallow to be mixed during winter convection, thus contributing to the surface nutrient field that fuels the annual spring phytoplankton bloom. A depth of 100 m is also 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, on the one hand, 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 semiconservative water property (with temperature and salinity). On the other hand, 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; 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: $[\mathrm{NO}_3^-] = 12.24\ \mu\mathrm{M}$) 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; $[\mathrm{NO}_3^-] = 14.98$ and 12.62 μM) and during a NOAA survey cruise that sampled water from 100 m at a station directly beside the mooring (23 November 2013; $[\mathrm{NO}_3^-] = 14.43\mu\mathrm{M}$). For comparison, we also present profiles at stations sampled in Georges Basin and the Northeast Channel during that same November 2013 NOAA survey cruise. The ISUS sensor failed in early December 2013, after nearly 6 months of reporting real-time data.

3. Results

Buoy data records of temperature, salinity, and density (density anomaly, 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 ~6°C and 10°C), salinity by 1.0 (between ~33.7 and 34.7), and sigma-*t* by approximately 0.4 kg m^{-3}; 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.

The temperature and salinity record at 200 and 250 m in Jordan Basin (Fig. 4) are dominated by interannual variability. Although there is some evidence of an annual cycle, we might have expected a stronger annual signal based on earlier reports that inflows of slope water to the Gulf of Maine reach a peak in the fall to early winter and slacken in the spring and summer (Bigelow 1927; Ramp, Schlitz, and Wright 1985; Brooks 1987; Smith et al. 2001). There were several periods of less than 1-year duration of distinct phases, or episodes, of either warmer and saltier or cooler and fresher water properties, as well as longer-duration episodes lasting a year, 2 years, and longer (i.e., a final episode of 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 approximately 6 months into the spring of 2004. Later in 2004 and again in 2005, there was a pair of relatively brief periods (~3–5 months) of very cool and fresh waters at both 200 and 250 m (<7°C and <33.75 *S*) separated by a brief period of 3 to 5 months of slightly higher temperatures and salinities. During the 2-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 an abrupt drop in temperature and salinity that lasted approximately 2.5 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, although fluctuating somewhat, has lasted throughout the remainder of the time series (until early 2014).

Also shown in Figure 4 is a plot of the North Atlantic Oscillation (NAO) winter index (December–March) that has been lagged 2 years (following Greene and Pershing 2003; Mountain 2012). 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 2 years later. Those data show no correlation with the 200 and 250 m temperature and salinity record over this

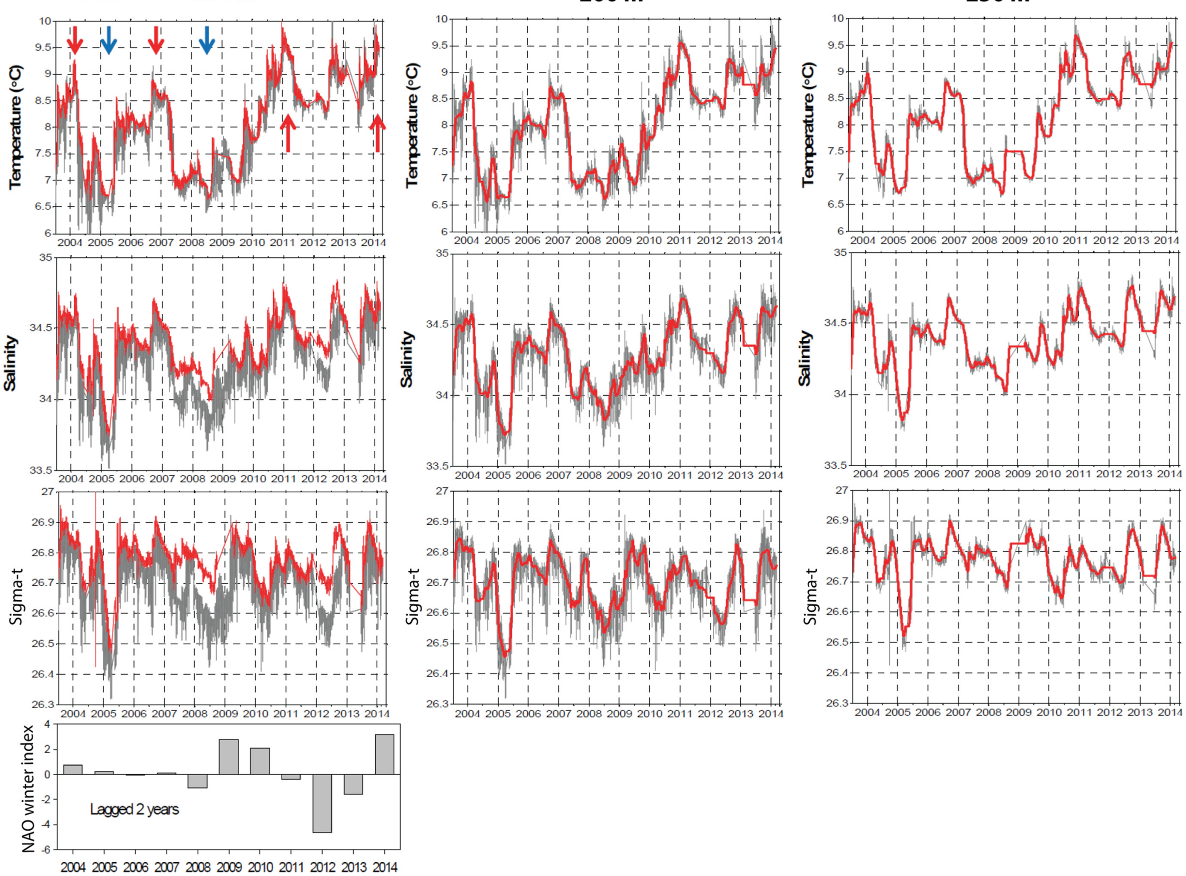

Figure 4. Temperature, salinity, and density (sigma-*t*) at 200 and 250 m in Jordan Basin at Buoy M of the University of Maine Ocean Observing System for the period 9 July 2003 to 10 March 2014. Data for both 200 and 250 m are plotted together in the first column for comparative purposes (gray = 200 m; red = 250 m). Data are plotted separately in the second and third columns, with red lines indicating the 30-day running average. Vertical dashed lines and year labels indicate 1 January 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 in first column is the North Atlantic Oscillation (NAO) winter index, for December–March, for each year 2002 to 2012 (from the National Center for Atmospheric Research)

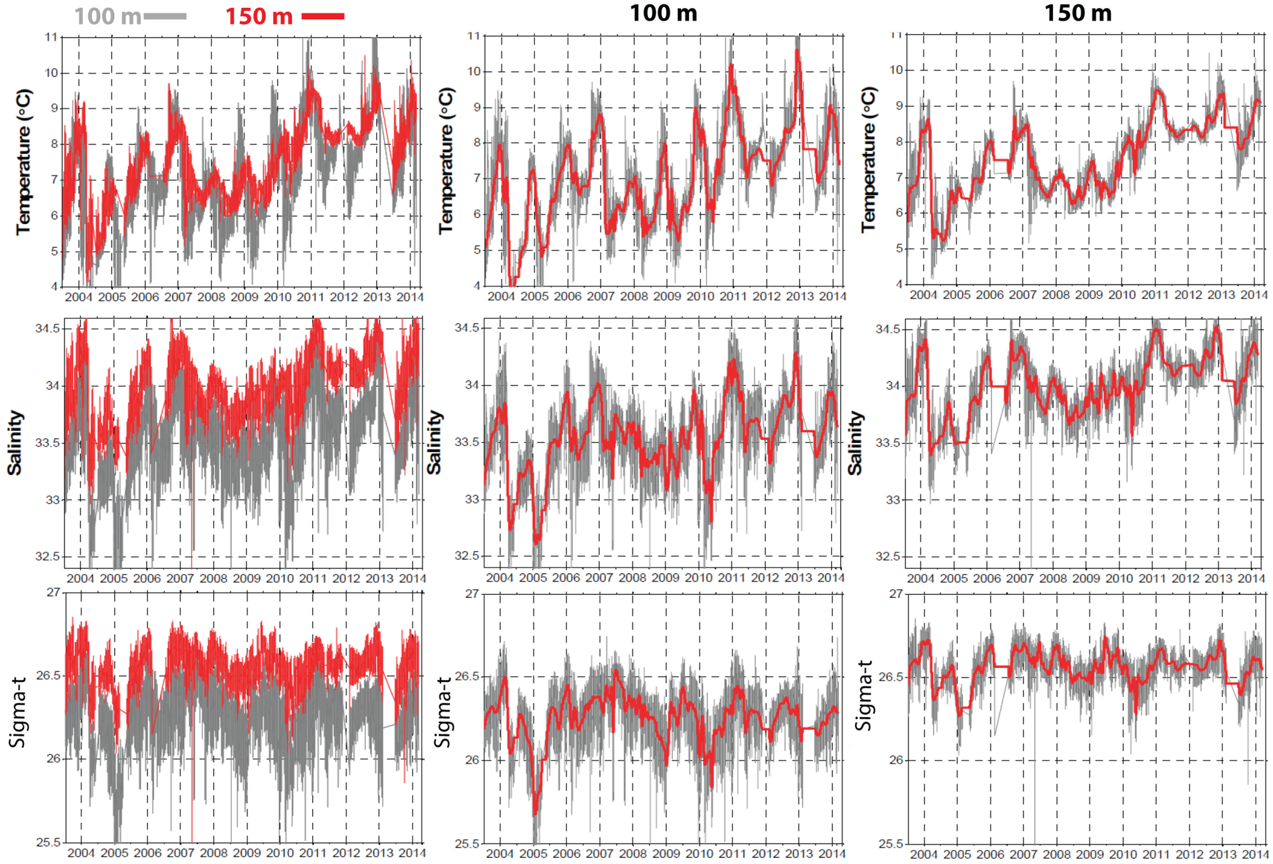

Figure 5. Temperature, salinity, and density (sigma-*t*) at 100 and 150 m in Jordan Basin at Buoy M of the University of Maine Ocean Observing System for the period 9 July 2003 to 10 March 2014. Data for both 100 and 150 m are plotted together in the first column for comparative purposes (gray = 100 m; red = 150 m). Data are plotted separately in the second and third columns, with red lines indicating the 30-day running average. Vertical dashed lines and year labels indicate 1 January for that year. Data were collected hourly, except for data gaps shown.

10-year period. This was unexpected because it has already been shown by a number of workers (reviewed in Drinkwater, Mountain, and Herman 1998, cited in Mountain 2012; Pershing et al. 2001; Drinkwater et al. 2003; Greene and Pershing 2003; Petrie 2007) that the relative contributions of the two slope water types, WSW and LSW, vary with the NAO. That is, the NAO, a phenomenon of fluctuating differences in atmospheric pressure between the Icelandic High and the Azores Low, 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 more cold, relatively fresh LSW to the Slope Sea, while at the same time, the north wall of the Gulf Stream shifts southward, allowing more LSW to penetrate farther to the southwest, making more 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 previously of NAO effects on the oceanography of the northwest Atlantic Ocean, Thomas, Towsend, and Weatherbee (2003) showed evidence of the NAO effects in hydrographic and nutrient profiles taken in the Northeast Channel in March 1997, 1998, and 1999; those results are replotted here (Fig. 6). Evidence of an LSW 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 unmodified LSW, based on water properties assumed by Mountain (2012) and others (6°C and 34.6 *S* for LSW, and 12°C and 35.4 *S* for WSW). In 1998, 2 years following an exceptionally low NAO winter index in 1996, LSW appeared to be the dominant water mass throughout much of the deep and bottom water column in the Northeast Channel and the interior Gulf of Maine, as discussed by Drinkwater, Mountain, and Herman (1998, cited in Mountain 2012). However, the cold water temperatures, less than 5°C at 200 m (Fig. 6), and relatively fresh salinities ($\leq$34.2 at 200 m) reflect either much lower temperatures for LSW source waters than those cited in the literature or significant mixing of LSW and WSW with a colder and fresher water mass. We suggest that SSW was an important component of waters entering the gulf through the Northeast Channel in 1998, mixing with and modifying the properties of LSW upstream of the channel, possibly on the continental slope where SSWs overlie 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 *S*, as can be seen in Figure 6.

Although 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 (Fig. 4). 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

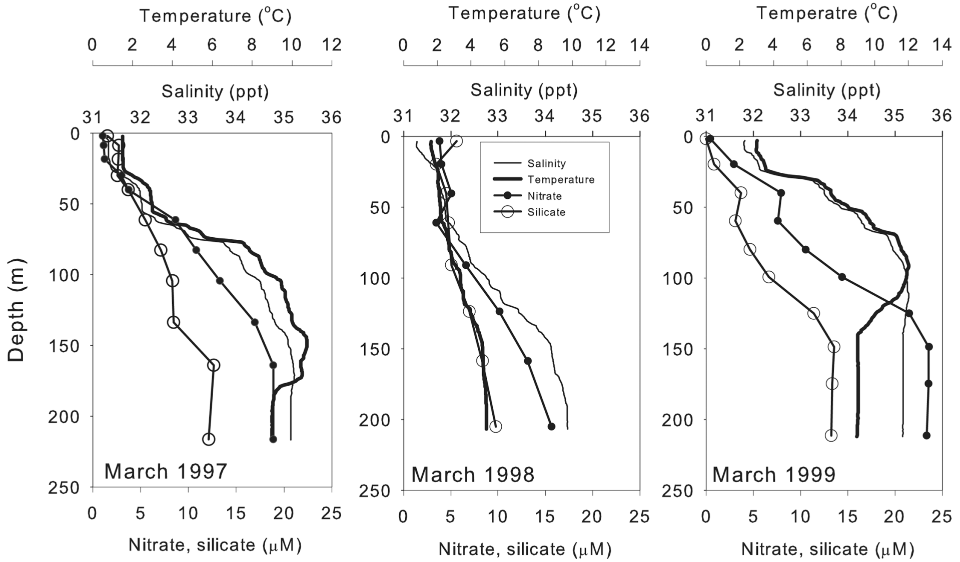

Figure 6. Profiles of temperature, salinity, nitrate, and silicate sampled at a station in the Northeast Channel in March 1997, 1998, and 1999; replotted after Thomas, Townsend, and Weatherbee (2003).

Table 1. Lag cross correlations of sigma-*t* (after Deese-Riordan 2009) between observations at Jordan Basin Buoy M and Buoy N in the Northeast Channel. The correlations were determined between the longest gap-free, overlapping time series at each depth. The degree of correlation and lags change considerably for different subsets of the time series, reflecting variation in the flow regime through the Northeast Channel and uncertainty in the route of channel waters to Jordan Basin.

Depths Buoy N: Buoy M	Lag (days)	Correlation Coefficient	P value
1m : 1m	41	0.55	0.045
20m : 20m	47	0.55	0.031
50m : 50m	86	0.53	0.045
100m : 100m	90	0.55	0.05
200m : 180m	105	0.75	0.045
250m : 180m	98	0.8	0.035

200 m during those episodes can only have resulted from an influx and/or deep mixing of coastal/shelf waters, most likely SSW, 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 multiyear patterns at 200 and 250 m but exhibit a wider range of values, with temperatures varying by approximately 5°C at 150 m over the 10-year record and more than 6°C at 100 m. The same is seen for salinity, which exhibits a wider range of values at 100 m than at 150 m. The greater short-term variability (1 day or less) in water properties at these shallower depths is, we expect, primarily the result of internal tides and internal solitary waves. The alternating patterns in water properties at 200 and 250 m are also evident at 100 and 150 m, with brief periods of cold and fresh waters in 2004–2005, a period of warmer and saltier conditions the following 2 years (in two peaks, in the winters of 2006 and 2007), followed by cooler and fresher waters between 2007 and late 2009 and a warmer, saltier period from late 2010 to the present. However, there are important differences: First, there is evidence of a stronger annual cycle in the shallower 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 annual influx of SSW 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 in 2004, 2005, and 2010 that are not evident at the deeper depths. Corresponding late-winter, early spring temperatures were colder in 2004 and 2005 and each spring from 2007 to 2010.

As shown in Table 1, the mooring data for Buoy M in Jordan Basin are coherent with 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 multiyear patterns of cool, low-salinity waters alternating with warmer, higher-salinity waters. However, those data for the Northeast Channel

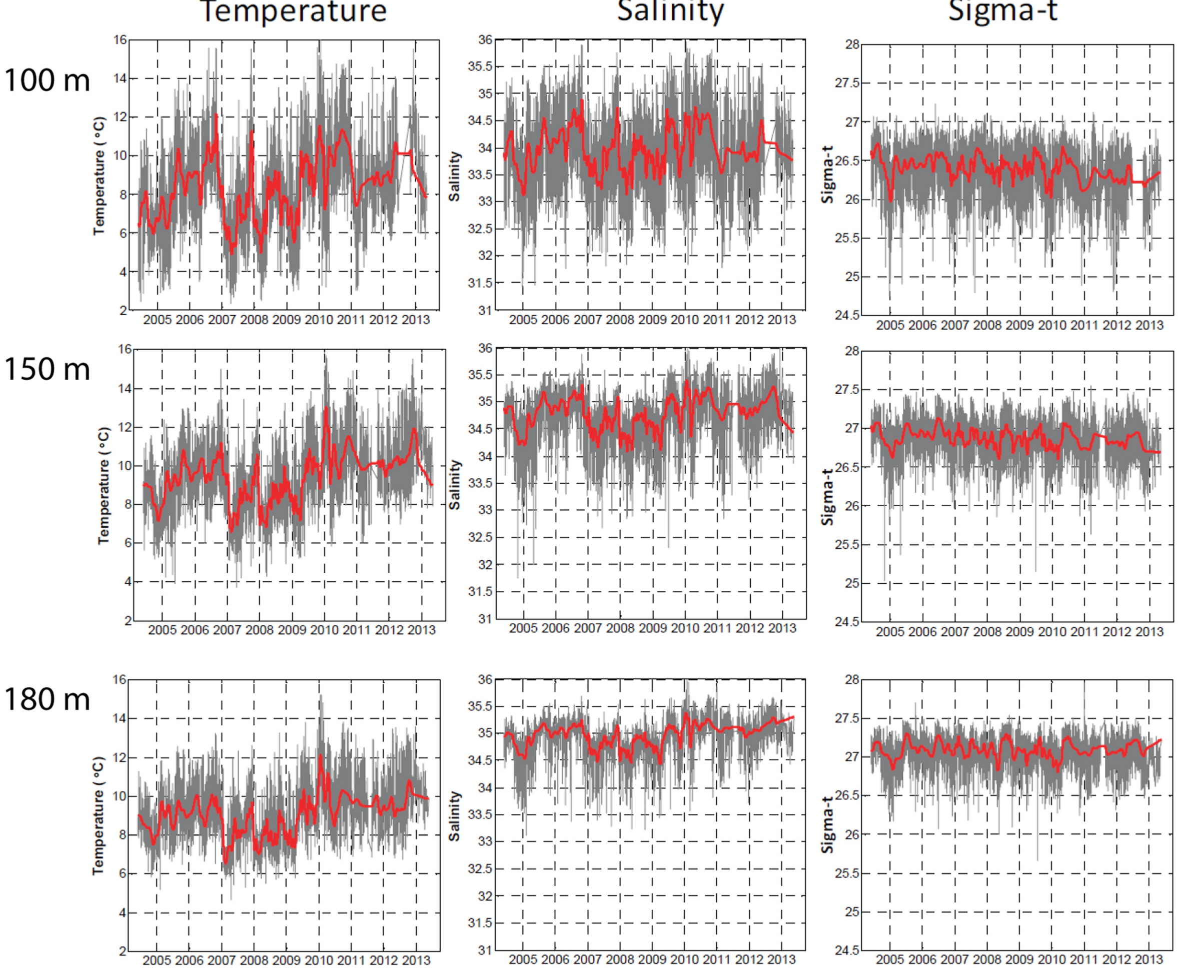

Figure 7. Temperature, salinity, and density (sigma-*t*) at 100, 150, and 180 m in the Northeast Channel at Buoy N of the University of Maine Ocean Observing System for the period 3 June 2004 to 7 May 2013. The vertical dashed lines and year labels indicate 1 January for that year. Data were collected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

mooring exhibit a wider range of values than those in Jordan Basin; temperatures vary by approximately 6°C and 2.0 *S* at 100 m in the Northeast Channel, which is approximately twice that at the same depth in Jordan Basin. The variability is greater at the shallower depths for both mooring sites. The more variable temperatures and salinities in the Northeast Channel, compared with Jordan Basin, are likely the result of the Northeast Channel's closer proximity to the shelf edge and source water masses. Gulf Stream rings, variability in the flow of SSW over the Northeast Channel, the magnifying effect of channel processes, and proximity to the foot of the shelf-slope front likely all combine to increase variability at the Northeast Channel buoy site. Also, as discussed previously, 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. Perhaps more importantly, as reported in Pettigrew et al. (2008), Pettigrew, Fikes, and Beard (2011), and Smith et al. (2012), since the early 2000s there are persistent periods of deep (>100 m) outflow on the eastern side of the Northeast Channel as well, which would suggest that outflow on the western side is even stronger. Nonetheless, the Northeast Channel data record is coherent with the Jordan Basin record (Table 1), with a lag time of 1 to 4 months, as was shown earlier by Deese-Riordan (2009). A notable exception is 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 depths of an increase in temperature and salinity (an influx of slope water) during the summer-to-winter period of 2013–2014; that increase is especially rapid at depths of 100 and 150 m (Fig. 5). As shown by Deese-Riordan (2009), the inflow of slope water into Jordan Basin typically peaks in early fall, as has also been reported earlier (Bigelow 1927; Ramp, Schlitz, and Wright 1985; Brooks 1987; Smith et al. 2001). To examine more closely the summer-to-winter period in 2013–2014, data from 100 m for the area are replotted in Figure 8, along with nitrate concentrations at 100 m as reported by the Satlantic ISUS nitrate sensor. A noticeable feature in Figure 8 is the dramatic increase in temperature and salinity over a period of a few days in July 2013, when the temperature increased by 2°C, from approximately 6.5°C to 8.5°C, and salinity increased by 0.5, from approximately 33.3 to 33.8, which was accompanied by a sharp drop in nitrate concentrations, from approximately 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 third semiconservative water property (with temperature and salinity), we would have incorrectly assumed that this event was an intrusion of deep WSW. That the nitrate concentrations dropped, and did not increase, as would have been the case with nutrient-rich WSW, indicates this event is most likely an influx of modified Gulf Stream ring water, the source waters of which, beyond the shelf edge, have nitrate concentrations that range from 0 to approximately 3 μM over the top 350 m (e.g., Townsend et al. 2010). The spikes in temperature and salinity in Figure 8 reflect Gulf Stream ring water that has been modified in transit to Jordan Basin, mixing with interior Gulf of Maine waters and becoming colder

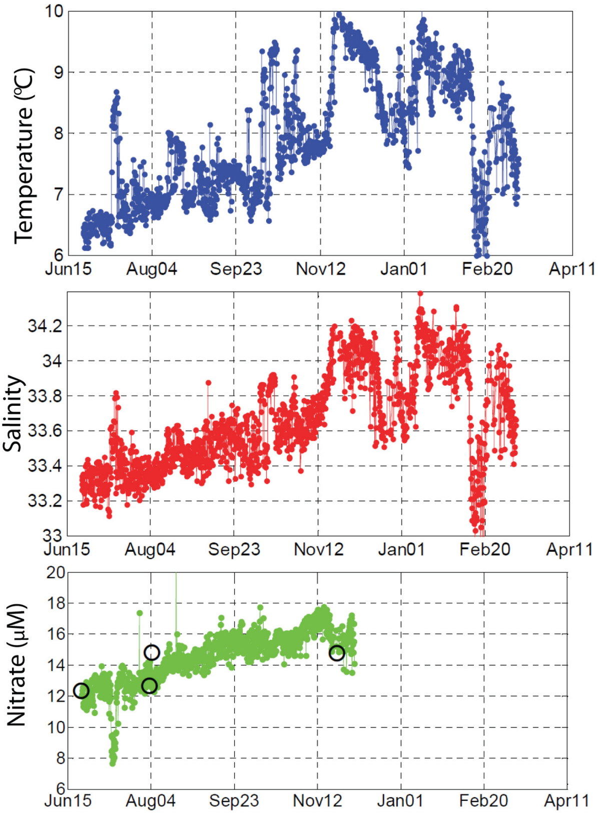

Figure 8. Temperature, salinity, and nitrate data collected at 100 m at Buoy M, in Jordan Basin, Gulf of Maine, from the time of deployment, 23 June 2013, to 10 March 2014. Nitrate data were collected six times per day; temperature and salinity data, recorded hourly, were subsampled to match the nitrate data. The in situ ultraviolet spectrometer 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 (23 June 2013; $NO_3 = 12.24\,\mu M$) and again on two other occasions (4 August, within 3 nautical miles of the site; $NO_3 = 14.98$ and $12.62\,\mu M$; and 23 November 2013, beside the mooring; $NO_3 = 14.43\,\mu M$). These are plotted as open black circles.

and fresher than the original values. Nitrate concentrations increased from their presumed initial values of less than 3 µM to approximately 8 µM, which are significantly lower than the surrounding resident waters (∼12 µM). A similar but less pronounced Gulf Stream ring water event can perhaps be seen in late November–December (Fig. 8).

Observations of intrusions of modified Gulf Stream water into the Gulf of Maine are not new. For example, Townsend et al. (2014) presented evidence of modified Gulf Stream waters (17.5°C and 35.6 *S*) inside the 200 m isobath on the southern flank of Georges Bank in

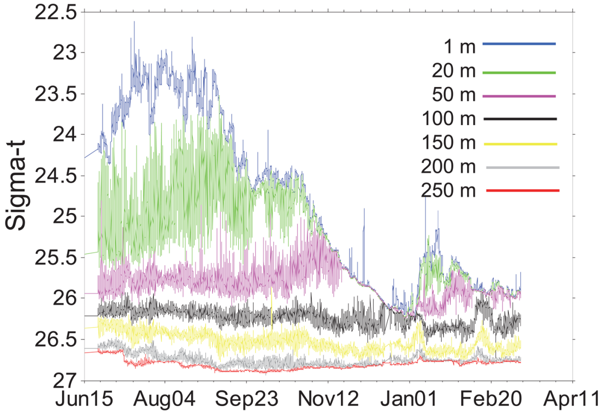

Figure 9. Density anomaly (sigma-*t*) at 1, 20, 50, 100, 150, 200, and 250 m in Jordan Basin at Buoy M of the University of Maine Ocean Observing System for the period 23 June 2013 to 10 March 2014.

the summers of 2007 and 2010, but it was Brooks (1987, 8183) who first provided an in-depth analysis of Gulf Stream warm-core ring water as it “contributes to or modifies the inflowing slope water” in the Northeast Channel. He noted that intrusions occur mostly at subsurface depths, making those waters difficult or impossible to identify in satellite imagery of sea surface temperatures, but he cited Smith (1978) who estimated that approximately six warm-core rings affect the Scotian Shelf each year. By extension, Brooks (1987) argued that Gulf Stream rings, although intermittent, are potentially important contributors to water mass properties in the Gulf of Maine and on Georges Bank. To our knowledge, the observation we present here, supported by nitrate data in addition to temperature and salinity, is the first time that modified Gulf Stream water has been detected in Jordan Basin in the interior Gulf of Maine, more than 200 km from the entrance to the Northeast Channel.

Apart from the evidence of modified Gulf Stream water, the data in Figure 8 for the summer-to-winter period of 2013–2014 reveal an overall increase in temperature, salinity, and nitrate, indicative of the fall influx of warm and salty (and high-nutrient) WSW discussed by Deese-Riordan (2009) and others cited previously. Salinities at 100 m exceeded 34.0, and nitrate concentrations reached 17 μM by November. The nitrate increase over the fall–early winter period was not the result of convective mixing with deeper, nutrient-rich waters below 100 m, evidence of which can be seen in the plot of sigma-*t* at each of the Jordan Basin sample depths (1, 20, 50, 100, 150, 200, and 250 m) over that time period (Fig. 9). Wind and convective mixing are evident in the surface waters in September and October, and by November the water column has become vertically mixed to 50 m; deep wind and/or convective mixing to 100 m are evident in late December (2013) and early January (2014) when the temperatures and salinities at 100 m drop to approximately 8°C and 33.6

(Fig. 8) and the water column is isopycnal from the surface to 100 m (Fig. 9); this deep mixing happened after nitrate concentrations at 100 m reached 17 μM in late November, after which the ISUS nitrate sensor failed (mid-December). The water column became restratified in January and February (Fig. 9) as a result of an influx of colder (5°C to 7°C) and fresher (salinity 32.5 to 33.4) SSW from the surface to 50 m (data not shown), which was followed by a wind and/or convective mixing event on approximately 15 to 20 February 2014, when both temperatures and salinities at 100 m became abruptly colder and fresher.

The evolution of water properties in Jordan Basin from summer 2013 to winter 2014 is best shown by the temperature-salinity (T-S) diagrams in Figure 10, in which we present monthly subsamples from each depth (e.g., 1, 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 is 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" shape. (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 in fall and winter, but at the same time, we can see by October that the water properties at 50 and 100 m appear to be stretched, as they become not only warmer but also saltier as indicated by the arrows in Figure 10. We interpret these changes as the result of WSW flowing into the mooring location, creating what appears as a wavelike overriding of 100 m water upward and to the right in the T-S diagram, as those waters become progressively warmer and saltier, reflecting their WSW end member. The waters beneath, at 150 m and deeper, remain unaltered from October to December. By January, convective mixing has reached 100 m, and the inflowing WSW begins to mix with the deeper waters. Also in January, evidence of an intrusion into Jordan Basin of cold and fresh SSW can be seen at depths from the surface to 50 m, and its having been mixed to 100 m by February. This produces the extension of T-S data pairs to the lower left of the T-S diagrams in January and February (Fig. 10).

It is important to point out that the 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) showed 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 approximately 30 and 100 m. The influx and mixing of WSW in the fall–winter of 2013–2014, combined with the earlier deep influx of WSW that began in summer, 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 (Fig. 5).

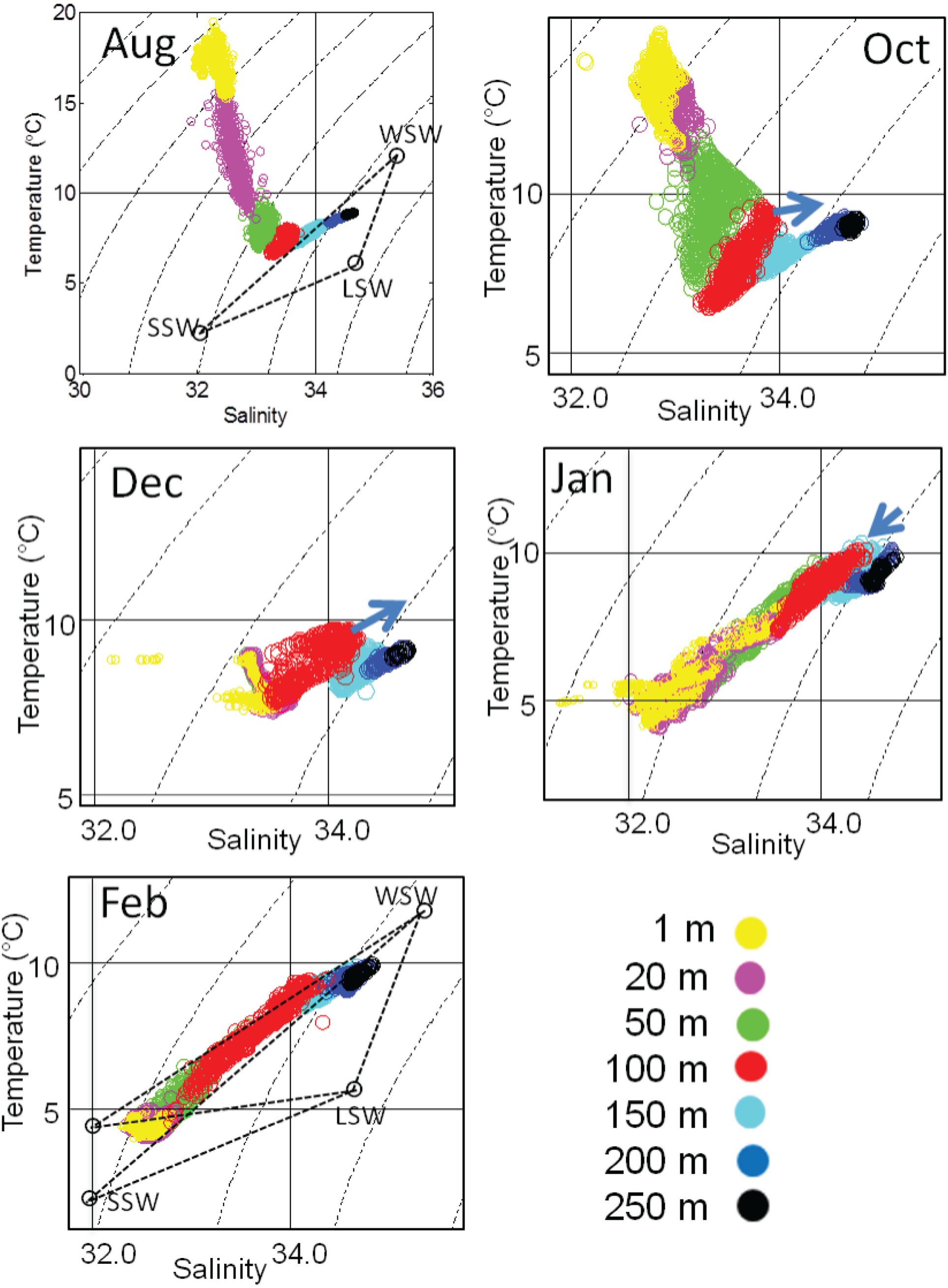

Figure 10. Temperature-salinity (T-S) diagrams for data collected at 1, 20, 50, 100, 150, 200, and 250 m (color-coded) in Jordan Basin at Buoy M of the University of Maine Ocean Observing System for the months indicated in 2013 and 2014. The full T-S plot is given for August 2013; the characteristic temperature and salinity 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 34.0 S are given in each panel; the blue arrows indicate the movement of the 100 m T-S data pairs between that month and 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.

4. Discussion

The results presented here demonstrate that variability in proportions of the three water masses that enter the Gulf of Maine—SSW, LSW, and WSW—are important to the gulf's bulk water properties. 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, Mountain, and Herman 1998, cited in Mountain 2012; Pershing et al. 2001; Drinkwater et al. 2003; Greene and Pershing 2003; Petrie 2007). It is worth noting that Bigelow (1927) was quite adamant that the previously assumed role of waters of Labrador Sea origin as a "cooling agent" in the Gulf of Maine was based more on theoretical 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 freshwaters). Although today SSW is 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 seen in Figures 4 and 5, deep and bottom water salinities in Jordan Basin commonly drop to below 34.6, the characteristic salinity of LSW, and, of course, well below 35.4, the characteristic salinity of WSW (Gatien 1976; Mountain 2012). Influxes and mixing of LSW cannot be lowering the salinities to these values, leaving shelf waters—SSW and Gulf of Maine surface waters, with their lower salinities from local river runoff—as the possible sources of freshwater. 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 SSW 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), who showed that deep (>100 m) water temperatures, salinities, and concentrations of nitrate and silicate in the Gulf of Maine have changed over time. 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, a result of a greater proportion of, and deep mixing of, SSWs as compared with LSW and WSW. They speculated 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 United States (Greene et al. 2012). It is likely that, as shelf and slope waters mix off Labrador and Newfoundland and flow along the continental shelf at all depths from the

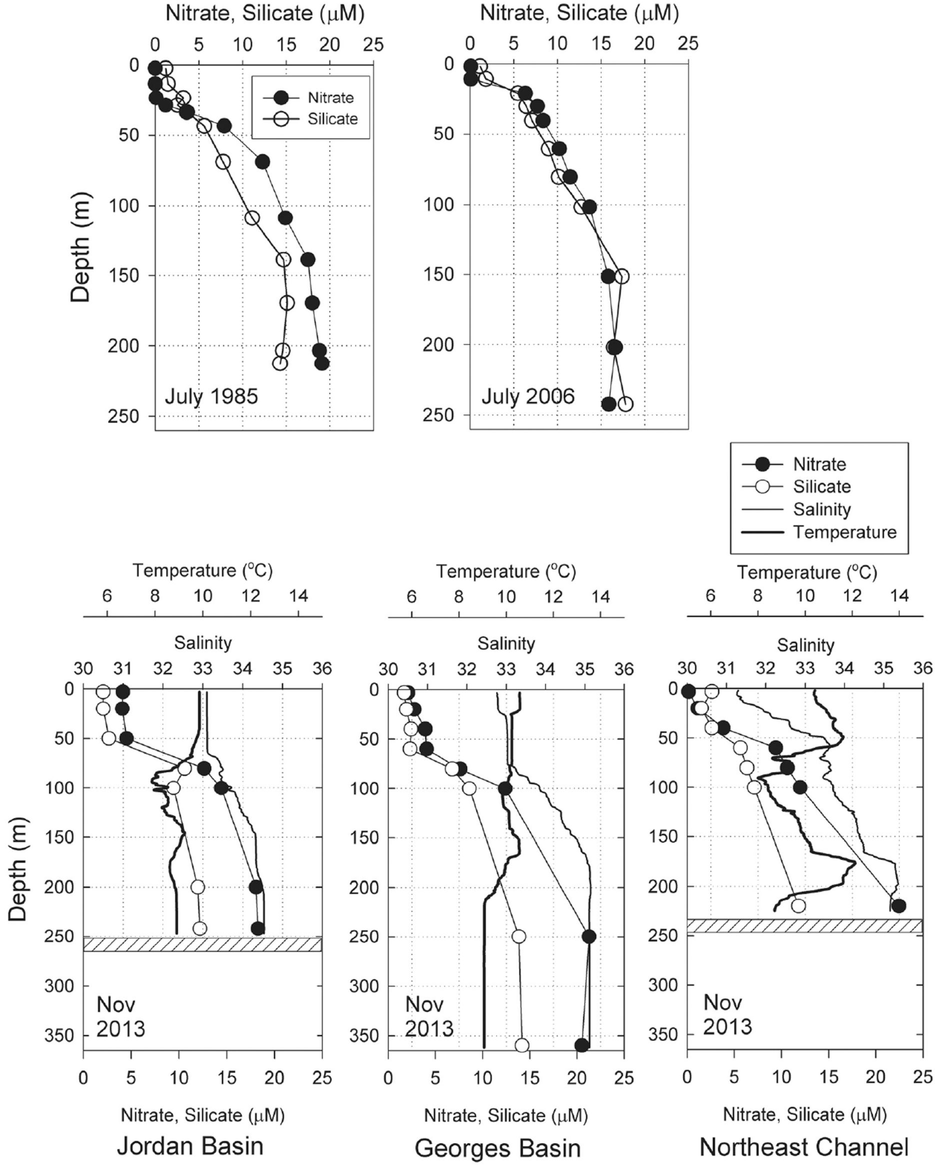

Figure 11. Top panels show concentrations of nitrate and silicate at a station in Jordan Basin in July 1985 and July 2006 (after Townsend et al. 2010). Bottom panels show temperature, salinity, nitrate, and silicate profiles at stations in Jordan Basin, Georges Basin, and the Northeast Channel in November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

Grand Banks of Newfoundland to the Gulf of Maine, the nutrient loads become altered by both benthic denitrification, which depletes nitrate concentrations (e.g., Christensen, Townsend, and Montoya 1996), and accumulations of terrestrially derived silicate in river runoff (Townsend et al. 2010). Recent studies have shown that altered nutrient fluxes to the Gulf of Maine 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 an abbreviated 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). These results are in keeping with those reported in Townsend et al. (2014) who examined nutrient and hydrographic data collected on 10 survey cruises in the Gulf of Maine in 2007, 2008, and 2010 and showed examples of water properties and corresponding concentrations and relative proportions of nitrate and silicate; colder and fresher water masses had silicate concentrations that equaled or exceeded nitrate, but the opposite held for warm and salty water masses. Therefore, the periods of alternating differences in nitrate and silicate concentrations in the gulf reported previously are most likely the result of episodic differences among years in the proportions of SSW and the sum of the two slope waters, LSW and WSW.

We examined these 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), using T-S analyses and a three-point mixing triangle, as described by Mountain (2012) and illustrated in Figure 12. Although we use the literature-cited T-S values for WSW and LSW source waters, it is important to point out that there is a range of values for LSW and WSW, which we show in Figure 12 as T-S envelopes for WSW and LSW using values given by Petrie and Drinkwater (1993), after Gatien (1976). Our analyses of average water properties during six peak times of alternating episodes at 250 m in Jordan Basin, as identified in Figure 4 and given in Table 2 and Figure 13, reveal that they are principally a function of the relative proportions of WSW and SSW, which covary with one another. That is, waters at 250 m in Jordan Basin have mixed with a fresher water mass (e.g., SSW) that falls outside the envelope of the values described for LSW. Although the errors in water mass proportions given in Table 2 are likely significant (given the uncertainties in the three points comprising the mixing triangle in Fig. 12), those analyses show that the warm and salty episodes at 250 m are the result of proportionally greater volumes of WSW (54%–69%) and lesser volumes of SSW (13%–18%), whereas the colder and fresher episodes were the result of greater volumes of SSW (30%–54%) and lesser WSW (31%–33%). The volumes of LSW, which ranged from 13% to 39% of the total, were unrelated to the episodes (Fig. 13). Because the extremes in water properties at 100 m during these six episodes fall outside

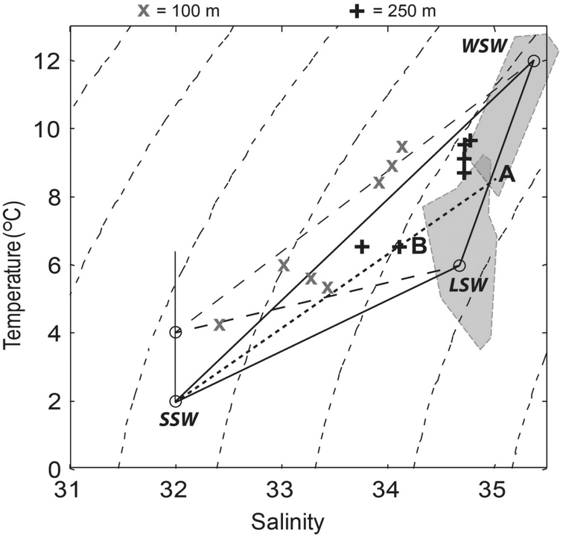

Figure 12. A temperature-salinity (*T*-*S*) diagram with dashed lines of constant density, on which are plotted the *T*-*S* properties of the three water masses (WSW, LSW and SSW), connected to one another by a solid line forming a mixing triangle. The characteristic water properties of the three water masses (Mountain 2012, and references therein) are as follows: 6°C and 34.6 *S* for LSW, 12°C and 35.4 *S* for WSW, and 2°C and 32.0 *S* 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. We have also plotted a second mixing triangle with the same values for WSW and LSW but with a value for SSW of 4°C and 32.0 *S*, 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 (gray-filled areas) for WSW and LSW using the range of values given by Petrie and Drinkwater (1993), after Gatien (1976). Average values of temperature and salinity for each of the episodes identified in Figure 4 and Table 2 (warm and salty and cold and 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 are 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 m *T*-*S* data lie outside the solid-line mixing triangle and inside the modified mixing triangle (discussed in text).

the *T*-*S* envelope defined by SSW, LSW, and WSW (Fig. 12), similar calculations were not performed. Qualitatively, however, we can see that were we to extend the SSW point in the mixing triangle in Figure 12 from 2°C to 4°C, to account for seasonal variability in temperatures of these shallower waters, most of the data points at 100 m would be captured. Average *T*-*S* pairs for episodes at 100 m plot well to the left of corresponding values for

Table 2. Percentage volumes of Scotian Shelf Water (SSW), Labrador Slope Water (LSW), and Warm Slope Water (WSW) during each of the six extreme temperature and salinity events (warm/salty and cold/fresh) in waters at 250 m in Jordan Basin, indicated in Figure 4, determined using the three-point mixing scheme in Mountain (2012).

Event	Year	Season	Ave. Temp. (°C)	Ave. Salinity	% SSW	% LSW	% WSW
1. Warm/Salty	2004	Winter/Spr.	9.2	34.70	15	22	63
2. Cold/Fresh	2005	Summer	6.6	33.75	54	13	33
3. Warm/Salty	2006	Fall	8.8	34.70	13	33	54
4. Cold/Fresh	2008	Summer	6.6	34.10	30	39	31
5. Warm/Salty	2011	Winter/Spr.	9.7	34.75	15	13	72
6. Warm/Salty	2014	Winter	9.5	34.70	18	13	69

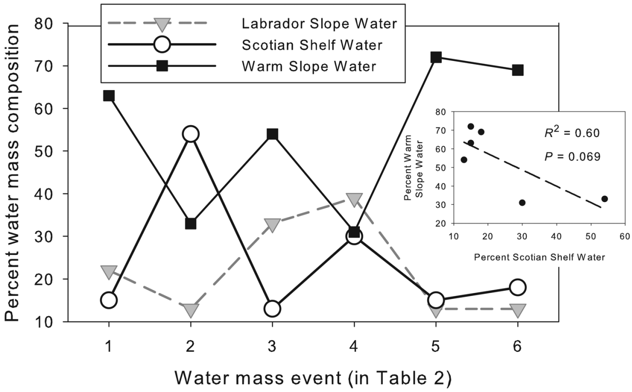

Figure 13. Plot of water mass percentages for each of the six water mass events at 250 m in Jordan Basin (warm and salty and cold and fresh) given in Table 2 and plotted in Figure 12. A linear regression of percent Warm Slope Water as a function of percent Scotian Shelf Water is given, along with the R^2 (0.60) and P value (0.69).

250 m, and the cool and fresh events at 100 m, for example, reflect a volume of some 50% to 90% SSW, and as much as 30% to 40% SSW even during warm and salty events.

These T-S analyses show that in order to explain the water property variations in Figure 4, for example, SSW must be a significant component of the deep and bottom waters in Jordan Basin. Evidence of deep mixing of SSW can also be seen in the Northeast Channel (Fig. 7) where salinities at 180 m are often lower than 34.6 (characteristic of LSW source waters), especially between the years 2007 and 2009. Deep mixing of SSW is clearer at 150 m and 100 m in the Northeast Channel, where salinities are fresher still. Not only do lower salinities signal that SSW must have, at some point, mixed with the waters at deep (200 and 250 m) and intermediate (100 and 150 m) depths in Jordan Basin, but so do temperatures, which are colder than the presumed bottom source waters entering through the Northeast Channel.

Interannual variations in water properties, especially water temperatures, in the Gulf of Maine have been previously attributed to the NAO and its influence on relative proportions of WSW and LSW, as we alluded to previously. It has also been suggested that differences in the nutrient loads in these two slope waters may influence biological productivity (Thomas, Townsend, and Weatherbee 2003; Townsend et al. 2006; Townsend and Ellis 2010). Although our results strongly implicate the influence of colder and fresher SSW on the deep and bottom waters of Jordan Basin, it is also possible that 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. In any event, SSW appears to have a more important role than previously realized in water mass characteristics (and nutrient concentrations) at and below depths of 100 m in Jordan Basin. If we are correct, then it is 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, there was a positive correlation between NAO and water temperatures below 100 m in the Gulf of Maine, but not after the mid-1990s (Townsend et al. 2010). 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 (2012) 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 water mass properties in the Northeast Channel and Jordan Basin (Table 1) would indicate that, indeed, a significant fraction of the waters in Jordan Basin passed through the Northeast Channel, but that they either became, or had previously been, significantly mixed with SSW.

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 inflows of LSW and greater inflows of SSW, which have not only increased in recent years but also exhibited unpredictable variations (e.g., Smith et al. 2012). 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 source waters, and a broader range must be assumed, or a fresher and cooler SSW mass must be part of the mixture. SSW, 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 eastern Nova Scotian Shelf (Petrie and Drinkwater 1993; Loder et al. 2001), 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 suggest that recent increases in SSW fluxes to the Gulf of Maine may be coupled to freshwater discharges upstream and their influence on baroclinic shelf currents, from Labrador to the Nova Scotian Shelf. In addition, changes in the transport of the Nova Scotia Current and fluxes of low-salinity waters to the Gulf of Maine may also be related to the wind field over Nova Scotia, as recently shown by Li et al. (2014). The end 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, 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 variable wind fields and/or upstream meltwaters, and how the concentrations of silicate and nitrate change while in transit along the continental shelf. 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 have also been influenced by variable SSW fluxes.

Acknowledgments. We gratefully acknowledge the unequaled expertise and hard work of John Wallinga, Robert Stessel, and Linda Mangum, as well as the University of Maine Mooring Group, without whom the kinds of insights into coastal ocean processes that we report here would be impossible. Special thanks go to Dr. Kate Hubbard of the Florida Fish and Wildlife Conservation Commission and Dr. Jon Hare of NOAA, Narragansett Laboratory, for collecting water samples for nutrient analyses. Funding was provided by grants from NOAA and the University of Maine. DJM was also supported by the Woods Hole Center for Oceans and Human Health through National Science Foundation grant OCE-1314642 and National Institute of Environmental Health Sciences grant 1P01ES021923-01.

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Received: *13 August 2014*; revised: *20 May 2015*.