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Spatial and temporal variability in the $\delta^{18}O_w$ and salinity compositions of Gulf of Maine coastal surface waters

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ABSTRACT

Hydrographic variability and dynamics in the Gulf of Maine are examined through the investigation of $\delta^{18}O_w$ and salinity properties of coastal surface waters. Data from Gulf of Maine waters sampled over a decade, from 2003 to 2015, including a suite of samples that were collected monthly from April 2014 to March 2015, are presented. These water samples fall on a mixing line between Maine River Water (MRW) and Scotian Shelf Water (SSW). However, slope waters likely also contribute to these surface waters. The seasonal variability in water samples collected during 2014 and 2015 indicates the strong influence of river runoff on coastal Gulf of Maine surface water properties. The coastal Gulf of Maine mixing line presented in this paper is a needed baseline for reconstructing hydrographic variability in bicarbonates using oxygen isotopes.

1. Introduction

The Gulf of Maine, a semi-enclosed sea on the eastern continental shelf of North America, sits near the intersection of two major North Atlantic currents: the Gulf Stream and the Labrador Current. Gulf of Maine hydrographic properties are therefore influenced by the dynamics and composition of these major currents. Reconstructing these hydrographic properties using proxy climate archives such as corals (Sherwood et al., 2011) and ocean quahogs (Wanamaker et al., 2008) has the potential to be a valuable indicator of the past behavior of these important North Atlantic currents. Before past and current hydrographic changes in the broader region can be interpreted from hydrographic changes seen in the Gulf of Maine, Gulf of Maine hydrographic dynamics and the influence of these dynamics on water properties must be comprehensively understood, both for off-shore and coastal locations. The composition (temperature, salinity and oxygen isotope values) and origin of water masses contributing to the Gulf of Maine water properties, as well as the water properties of several off-shore sites have been described in detail by numerous authors (Bigelow, 1927; Gatien, 1976; Fairbanks, 1982; Smith, 1983; Chapman et al., 1986; Chapman and Beardsley, 1989; Brown and Irish, 1993; Smith et al., 2001; Houghton and Fairbanks, 2001). Here, we focus on the use of oxygen isotopes and salinity in determining the hydrography of the Gulf of Maine coastal system.

1.1. $\delta^{18}O$ and salinity as conservative water mass tracers

Because the oxygen isotopic signature of water ($\delta^{18}O_w$) depends on the latitude of origin (Craig, 1961) and is not changed by biological processes during transport, $\delta^{18}O_w$ is considered a conservative property of water masses. $\delta^{18}O_w$ has a positive linear relationship with salinity, which is another conservative property of water masses. This relationship between salinity and $\delta^{18}O_w$ (referred to as a "mixing line" in this paper due to its indication of the mixing of two or more water masses) can therefore be used to determine water mass origin and mixing in any given region, such as the Gulf of Maine (Fairbanks, 1982).

There have been numerous studies that use oxygen isotopes and salinity as conservative tracers of water masses that are thought to contribute to the composition of Gulf of Maine waters. We will first review this work before discussing specific oxygen isotope and salinity studies within the Gulf of Maine.

1.2. Regional water mass composition

The Gulf of Maine is fed by several different water masses which have been described by their temperature, oxygen isotope and salinity signatures (Table 1). The general origin of these water masses is shown in Fig. 1. Deep waters in the Gulf of Maine have been shown by numerous authors to be composed of Labrador Slope Water (LSW) and Warm Slope Water (WSW). LSW is generally considered deep (greater than 100 m) water that is transported by the southwestward flowing

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Table 1
Properties of water masses composing Gulf of Maine waters. Bolded numbers are those chosen for figures and discussion in this paper. These water mass property definitions were largely determined from the end-members of salinity and $\delta^{18}O_w$ mixing lines derived from water samples collected on research cruises during the 1980s and 1990s. It is important to note that not all of these definitions take into account annual and monthly changes to the water masses but are meant to give rough estimates.

Water mass	Temperature (°C)	$\delta^{18}O_w$ (‰)	Salinity	Citation
Warm Slope Water (WSW)	10	0.4	35.2	Houghton and Fairbanks (2001)
	11.11 (potential)	**0.36**	**35.16**	Khatiwala et al. (1999)
Labrador Slope Water (LSW)	6	0.22	34.9	Houghton and Fairbanks (2001)
	3.28 (potential)	**0.22**	**34.80**	Khatiwala et al. (1999)
Scotian Shelf Water (SSW)		**−1.09**	**32.35**	Chapman et al. (1986)
Labrador Shelf Water (LShW)	0	−1.62	32.6	Houghton and Fairbanks (2001)
St. Lawrence River Water (SLRW)		−10.3	0	Khatiwala et al. (1999)
Arctic River Water (ARW)		−21	0	Khatiwala et al. (1999)
Maine River Water (MRW)		−10.89	0	Fairbanks (1982)
Gulf Stream Water		1.15	36.2	Fairbanks (1982)
	16	1.05	35.95	Houghton and Fairbanks (2001)

branch of the Labrador Current after it has split to divert some water into the Gulf of St. Lawrence (Chapman and Beardsley, 1989; Gatien, 1976). WSW is found at 0–400 m depths adjacent to the Gulf Stream and is warmer and more nutrient rich than LSW (Townsend and Ellis, 2010; Gatien, 1976). Both slope waters enter the Gulf of Maine via the Northeast Channel.

Shallow waters in the Gulf of Maine are composed of Scotian Shelf Water (SSW), which flows from the Scotian Shelf into the Gulf of Maine over Cape Sable (Smith, 1983; Chapman et al., 1986). By investigating

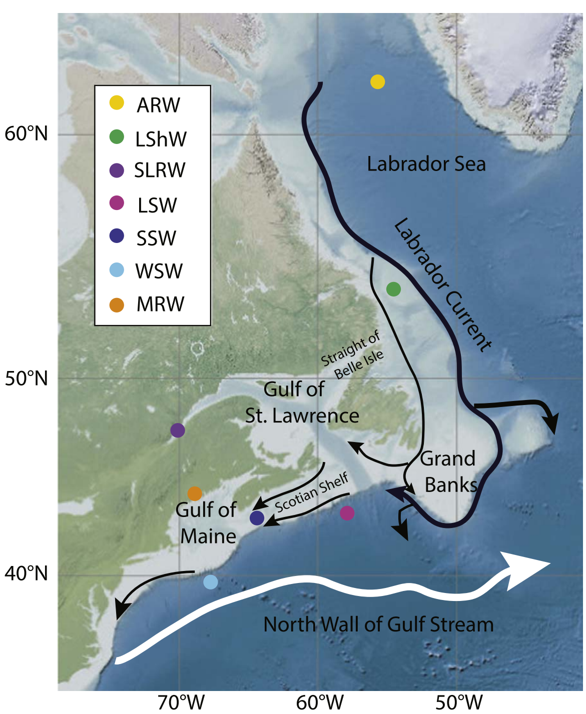

Fig. 1. Map of the general area of origin of water masses believed to contribute to the compositions of Gulf of Maine waters. These water masses include Arctic River Water (ARW; Khatiwala et al., 1999), Labrador Shelf Water (LShW; Khatiwala et al., 1999), St. Lawrence River Water (SLRW; Khatiwala et al., 1999), Labrador Slope Water (LSW; Chapman and Beardsley, 1989), Scotian Shelf Water (SSW; Smith, 1983, Chapman et al., 1986), Warm Slope Water (WSW; Gatien, 1976), Maine River Water (MRW; Fairbanks, 1982). The justification for choosing the location of origin for these water masses is described in the text. The approximate locations of major western North Atlantic currents are also shown: Gulf Stream (white arrow) and the Labrador Current (black arrows), after Chapman and Beardsley (1989) and Loder et al. (1998) and modified from Townsend et al. (2010). Width of arrows indicates the approximate relative strength of currents. Map modified from the NOAA National Geophysical Data Center (http://maps.ngdc.noaa.gov/viewers/fishmaps).

the $\delta^{18}O_w$-salinity relationship of waters on the Scotian Shelf, Khatiwala et al. (1999) determined that SSW was composed of LSW, Labrador Shelf Water (LShW) and St. Lawrence River Water (SLRW).

The majority of the freshwater in the Gulf of Maine originates in locations north of this region. The northern most possible source of freshwater to the Gulf of Maine is considered to be low-$\delta^{18}O_w$ Arctic River Water (ARW) flowing out of the Labrador Sea (Khatiwala et al., 1999). While Fairbanks (1982), Chapman et al. (1986), and Chapman and Beardsley (1989) all inferred the freshwater end-members ($\delta^{18}O_w$ of −21‰) of mixing lines derived from areas in and around the Gulf of Maine to indicate a freshwater source of ARW, Khatiwala et al. (1999) and Houghton and Fairbanks (2001) argue that this freshwater end-member is in fact the result of mixing between SLRW and LShW.

1.3. The $\delta^{18}O_w$ and salinity signatures of Gulf of Maine waters

Waters within the Gulf of Maine are the result of mixing between the water masses described in Section 1.2 as well as Maine River Water (MRW), which Fairbanks (1982) determined to have an average $\delta^{18}O_w$ of 10.89‰ (calculated by taking an annual average of the $\delta^{18}O_w$ composition of the Kennebec and St. John Rivers; Table 1). A brief review of work done on quantifying this mixing using the salinity and $\delta^{18}O_w$ composition of Gulf of Maine waters, as we do in this study, follows. Fairbanks (1982) sampled water at various depths in Wilkinson Basin, western Gulf of Maine, in January, May and August of 1981 (Figure S1A in the supplementary material). He found that Wilkinson Basin surface and intermediate waters (above 115 m depth) fall on a two water mass mixing line:

$$\delta^{18}O_w = 0.421S - 14.66 \tag{1}$$

This mixing line is very similar to the mixing line the author developed for the Scotian Shelf (Figure S1A in the supplementary material) and therefore suggests that the near surface and intermediate, non-coastal waters of the Gulf of Maine are primarily fed by SSW, as has been described in several other studies (Hopkins and Garfield, 1979; Smith, 1983).

Slope water, the composition of which Fairbanks (1982) determined from samples taken between Nova Scotia and Cape Hatteras, falls on a two-water-mass mixing line (Figure S1A in the supplementary material) between Gulf Stream water and fresh water that has a $\delta^{18}O_w$ value of −21.7‰, which the author took to indicate Labrador Sea origin. Samples of bottom water from Wilkinson Basin fall on this mixing line and suggest that bottom waters in the Gulf of Maine are composed of slope water (WSW and LSW), as separately determined by other authors (e.g. Ramp et al., 1985). The equation for this mixing line is: