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Spatial variability in stable isotope values of surface waters of Eastern Canada and New England

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SUMMARY

A total of 294 surface water samples were collected in Eastern Canada and the New England states of the USA in 2007, 2009, 2011, and 2013 and analyzed for $\delta^{18}O$ and δD values to investigate climatic controls on hydrology and to test whether isotope values of surface waters can provide a suitable calibration for evaluation of paleoenvironmental proxy data in this region. Results demonstrate that surface waters in this region exhibit latitudinal gradients, with some overprinting by regional trends. Surface water $\delta^{18}O$ and δD values range from −2.8‰ to −16.0‰, and from −23.8‰ to −118.5‰, respectively. Regression of all $\delta^{18}O$ and δD values yields a surface water line (SWL) ($\delta D = 7.53(\pm 0.11)\delta^{18}O + 3.81(\pm 1.12)$; $r^2 = 0.95$; $n = 294$), similar to slopes of 7.63(±0.06) and 7.96(±0.1) based on monthly and annual precipitation amount-weighted means for GNIP/CNIP stations in this study area. At smaller spatial scales evaporation and greater water residence time generate lake SWL with lower slope (7.50) than river SWL (7.80). At greater spatial scales, $\delta^{18}O$ and δD values of lakes and rivers show a more uniform distribution, thus reflecting the prevalence of regional over local hydrological effects.

Contour maps of surface water $\delta^{18}O$ and δD values exhibit more detail than existing global precipitation models and suggest (a) a progressive decrease in $\delta^{18}O_{H2O}$ and δD_{H2O} values towards higher latitudes via Rayleigh distillation and (b) generally higher $\delta^{18}O_{H2O}$ and δD_{H2O} values in Western Newfoundland likely due to its proximity to the ocean. Contour maps predict the average annual-amount weighted $\delta^{18}O$ and δD values of precipitation provided by GNIP/CNIP networks fairly well. It was also determined that recycled moisture supplies a significant proportion of precipitation in the southern/western parts of our study area, while evaporation could be a more dominant factor for interior Labrador. In addition, a strong agreement is observed between temperature and precipitation/surface water $\delta^{18}O$ and δD values, suggesting that $\delta^{18}O$ and δD values of surface waters can provide a suitable template and aid for ongoing paleoenvironmental research in this region.

1. Introduction

Stable isotope values of meteoric waters are commonly used as environmental tracers to track the hydrological cycle, water use, and spatial distribution of precipitation and thus have abundant applications and significant importance for hydrological (*e.g.* Gat et al., 1994; Gibson and Edwards, 2002; Telmer and Veizer, 2000; Welker, 2000; Yonge et al., 1989), atmospheric (*e.g.* Gedzelman and Lawrence, 1982; Hoffmann et al., 2000; Jouzel et al., 1997; Lawrence et al., 1982), and climate studies (*e.g.* Edwards et al., 1996; Kirby et al., 2002; Lachniet et al., 2009; Vuille and Werner, 2005). Owing to the intricate connection between hydrology and climate, stable isotope values of meteoric waters are also often directly and/or indirectly linked to interpretations of data retrieved from proxy climate archives (*e.g.* ice cores, lake/ocean sediment, plant material, and speleothems). Therefore, gaining a better understanding of stable oxygen ($\delta^{18}O_{H2O}$) and hydrogen (δD_{H2O}) isotope variability through space and time is useful for tracing variability in atmospheric circulation, regional precipitation, and latent heat transport (*e.g.* Diefendorf and Patterson, 2005; Johnson and Ingram, 2004), thus providing invaluable paleoclimatic evidence on a wide range of timescales.

$\delta^{18}O_{H2O}$ and δD_{H2O} values of precipitation (here referred to as $\delta^{18}O_{pt}$ and δD_{pt}) generally display well defined spatial and temporal variability that reflects geographical factors (i.e. latitude, altitude, and continentality) and climatic processes, such as the isotope values of the original water source, rainout mechanisms, temperature, air mass mixing, along with kinetic and equilibrium

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effects that occur during diffusion and water phase change (Daansgard, 1964; Rozanski et al., 1993). A strong linear correlation between $\delta^{18}O$ and δD of meteoric waters, first defined by Craig (1961) as $\delta D = 8\delta^{18}O + 10$ and later deemed the Global Meteoric Water Line (GMWL), represents the relationship between $\delta^{18}O$ and δD for fresh surface waters worldwide and it is a close approximation of $\delta^{18}O$ and δD in mean world annual amount-weighted precipitation (Rozanski et al., 1993). Another important parameter arising from the GMWL is deuterium excess, (*d* or D-excess), first defined by Daansgard (1964) as $d = \delta D - 8\delta^{18}O$. The D-excess refers to the amount of excess deuterium in the hydrogen versus oxygen relationship, arising from the greater mass difference between the hydrogen relative to oxygen isotopologues and has a typical, global average value of 10‰. Deviations from the global average D-excess value allow for additional assessments of environmental conditions during the time of vapor formation/rainout and quantifications of spatial and temporal moisture recycling (Araguás-Araguás et al., 2000).

Mid and high latitude regions are characterized by seasonality in $\delta^{18}O_{pt}$ and δD_{pt} in response to seasonal temperature variability and thus display significant agreement between $\delta^{18}O_{pt}$ and δD_{pt} and temperature at the precipitation sites (Rozanski et al., 1993). Paleoenvironmental archives from mid-latitude regions can therefore provide valuable information on past temperature variability and regional precipitation patterns, including variations in the seasonality of precipitation. Eastern Canada is a climatically dynamic region under a significant influence of the Atlantic Ocean that is rarely represented in paleoclimatic literature, but has a great potential for studying past climate dynamics. We hypothesize that temperature is the dominant control on precipitation and surface water $\delta^{18}O$ and δD values in this region. To test our hypothesis, we examined the spatial variability in $\delta^{18}O$ and δD values in precipitation collected at six stations within/near our study region by the Global and/or Canadian Network for Isotopes in Precipitation (GNIP/CNIP) and in 294 surface water samples (i.e. lakes and rivers; here referred to as $\delta^{18}O_{sw}/\delta D_{sw}$) collected in 2007, 2009, 2011, and 2013 from New Brunswick, Newfoundland and Labrador, Nova Scotia, Prince Edwards Island, and Quebec in Canada, several New England States (Maine, Massachusetts, New Hampshire, Vermont) and New York in the USA (Fig. 1 and Supplementary data Table 1). The overall goal of this project is to (a) test whether surface water samples can be used as an alternative to precipitation samples for determination of local meteoric water lines (LMWLs) in this region; (b) assess the importance of recycled moisture on hydrological budgets at smaller spatial scales; and (c) establish and compare $\delta^{18}O_{pt}/\delta D_{pt}$-temperature and $\delta^{18}O_{sw}/\delta D_{sw}$-temperature relationships. Results presented here can aid in the improvement and refinement of isotope hydrology for Eastern North America and significantly contribute to future interpretations of isotope-based paleoclimatological records from this region.

According to the Koppen-Geiger Classification, the southeastern region of Atlantic Canada (*e.g.* Nova Scotia and Newfoundland) has a humid continental climate, influenced by ocean–atmosphere dynamics due to proximity to the Atlantic Ocean and Labrador Sea. Our study region lies within the zone of prevailing westerly winds, strongly influenced by the adjacent ocean that modifies the climate throughout the year by keeping winter and summer air temperatures somewhat higher and lower, respectively, than more continental locations nearby. This region has one of the most variable weather profiles in North America. Owing to its location on the eastern side of North America and few topographical barriers, regional climate is characterized by short-term variability in weather systems and principal storm tracks. Two large ocean current systems, the Labrador Current and the Gulf Stream/North Atlantic Drift, strongly influence the properties of cold and warm air masses near this region, respectively. Northern Newfoundland and Labrador experiences a subarctic climate with little or no maritime influence due to its latitude and continentality (Environment Canada, 2010; Robertson et al., 1993).

In winter, our study region is influenced by the prominent low pressure system centered over southern Greenland, while central Labrador and Quebec are also influenced by the Arctic High pressure system (Fig. 1). In spring, the cold Arctic High becomes stronger, forcing a dominant northerly flow in northern sectors of the study region. In summer, the subtropical Bermuda High forces a predominant southwesterly airflow (Fig. 1). Summer cyclones are most common in Labrador. In fall, the general strengthening of the westerly airflow results in the cyclonic storm tracks becoming more active in the region (Robertson et al., 1993). Starting in October, strong meridional surface temperature gradients over this region, in addition to the land–ocean temperature contrast, can create a strong atmospheric baroclinity that can evolve into powerful coastal storms, referred to regionally as “Nor’Easters”. The position and intensity of storm tracks strongly influence weather and climate of Atlantic Canada and the New England States of the USA and are often associated with extreme wind and precipitation events that can cause significant environmental and economic impacts (Environment Canada, 2010; Zielinski, 2002).

Generally, our study area is characterized by evenly distributed, fairly high precipitation amounts (i.e. total annual precipitation ranges between 850 and 1500 mm, in coastal regions often ~1500 mm), high humidity, strong winds, fog, and an average annual temperature range (based on monthly averages) of ~25 °C (generally ~20 °C in coastal and ~30–35 °C in more continental locations). Approximately three-quarters of the total precipitation is rain, most abundant in fall (Environment Canada, 2011). A fairly uniform distribution of precipitation throughout the year suggests that no particular season should strongly dominate the recharge of lakes and rivers in most of the study region. In southern and southwestern parts of Newfoundland, however, winter precipitation is up to 9% higher than in summer. This trend decreases and reverses when approaching the interior Labrador, and it is approximately 16% higher in summer than in winter in Labrador City (Environment Canada, 2011).

Topography is not a significant factor in regulating weather and climate in this region, although it can help generate localized weather variations in the eastern parts of Newfoundland in combination with numerous bays and inlets (Robertson et al., 1993). The highest sample was obtained from a site at an elevation of 683 m (in Quebec); in contrast, several samples were obtained from sites near sea level (Supplementary data Table 1). The maximum latitudinal difference between the most northern and southern sampling points is 13.86°. Thus, latitude could be considered as an important factor affecting $\delta^{18}O_{sw}$ and δD_{sw} in this region.

Atlantic Canadian industries are highly sensitive to environmental variability, and directly linked to climate. Agriculture, forestry, fisheries, hydropower generation, mining/refining, transportation, and tourism are significantly affected by anomalous precipitation. Moreover, climate statistics demonstrate that despite sufficient and evenly distributed rainfall during the growing season there are still regular crop moisture deficits (Robertson et al., 1993). Therefore, in light of current and future climate change scenarios, there is a significant need for information on hydroclimatic anomalies in this region and their potential impact on water utilization, flood prevention, irrigation, natural resource processing, and hydro-electric power production.

2. Methods

In 2007, 93 samples were collected in Newfoundland, while in 2009, 141 samples were collected in Newfoundland, Labrador,