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# Salinity variability along the eastern continental shelf of Canada and the United States, 1973–2013

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A R T I C L E I N F O

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## A B S T R A C T

Continental shelf waters located off the east coast of Canada and the United States are part of a long shelf current system that is partly comprised of colder, less-saline waters originating from high latitudes, including waters from the North Atlantic sub-polar gyre, along with ice-melt and freshwater input from local rivers. A 41-year analysis (1973–2013) of near-surface salinity (NSS) using three hydrographic datasets (Bedford Institute of Oceanography “Climate”, NOAA/ESDIM, and Canadian Marine Environmental Data Service (MEDS)) allowed an examination of NSS variability within 11 continental shelf sub-regions, extending from the southern Newfoundland Shelf of eastern Canada to the DelMarVa/Hatteras Shelf of the United States. Although the periods of record containing sufficient data vary between sub-regions, regional mean NSS values are lowest within the Gulf of St. Lawrence and highest on the DelMarVa/Hatteras shelf, with largest annual variability within the Gulf of St. Lawrence. After removal of outliers, long-term linear trends computed from annual mean NSS were detected along the Newfoundland Shelf ($+0.011\ \mathrm{y}^{-1}$), Western Scotian Shelf ($-0.007\ \mathrm{y}^{-1}$), Gulf of Maine ($-0.014\ \mathrm{y}^{-1}$), Georges Bank ($-0.011\ \mathrm{y}^{-1}$), and DelMarVa/Hatteras Shelf ($+0.024\ \mathrm{y}^{-1}$). A long-term quadratic fit to annual mean NSS from the Eastern Scotian Shelf displays a salinity increase through 1992 of $+0.026\ \mathrm{y}^{-1}$, decreasing thereafter until 2013 by $-0.028\ \mathrm{y}^{-1}$. A quadratic fit for the Western Grand Banks displays a NSS increase through 2007 of $+0.022\ \mathrm{y}^{-1}$, decreasing thereafter through 2013 by $-0.006\ \mathrm{y}^{-1}$. Annual mean NSS from the Eastern Grand Banks, Tail of the Grand Banks, Gulf of St. Lawrence, and Middle Atlantic Bight display no long-term trends. Inter-annual variability (IAV) of NSS residuals shows similar small mean squared error (mse) of 0.02–0.04 for the four northern-most sub-regions (Newfoundland Shelf, Eastern, Tail and Western Grand Banks) and are correlated at 0-year lag. IAV of NSS residuals (mse) are larger for the Gulf of St. Lawrence (~0.19), Eastern and Western Scotian Shelf (~0.09–0.06), Gulf of Maine and Georges Bank (~0.08–0.06), Middle Atlantic Bight (~0.19), and maximal for the DelMarVa/Hatteras Shelf (~0.36), and are also correlated at 0-year lag, but are uncorrelated with the four northern-most sub-regions. Consideration of a simple “flux variation” model that includes along-shelf, altimeter-derived velocity anomalies measured upstream on the Western Scotian Shelf and the positive along-shelf mean salinity gradient between the Eastern Scotian Shelf and the DelMarVa/Hatteras Shelf, may explain the synchronous nature of NSS residuals for the southern-most 6 sub-regions. Furthermore, the flux variation model results in calculated NSS residuals that are within a factor of two of observed NSS residuals for the southern-most DelMarVa/Hatteras Shelf. Co-varying broad-scale coastal sea level and shelf break front position anomalies also support the flux variation model, as do *CMV Oleander* temperature anomalies across a limited Middle Atlantic Bight shelf region. Overall, the relationships between along-shelf observations of NSS and other shelf parameters support an existing wind-driven dynamical shelf model. Specifically, a flux variation model is able to describe IAV of NSS along a section of the Canadian and U.S shelf for periods greater than one year. In the future, this model may be able to provide useful indices of regime change as noted within the Northeast Shelf Large Marine Ecosystem by other workers.

## 1. Introduction

The continental shelf located offshore of eastern Canada and the northeastern United States encompasses the large relatively shallow area from the western Labrador Sea to Cape Hatteras, located between the shore and the shelf break inshore of the 200-m

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isobath). Mean flow of continental shelf waters over this shelf region is generally continuous and equator-ward due to buoyancy-driven currents forced by glacial and ice-melt water from northern sources including Hudson Bay and the Labrador and Newfoundland shelves (Myers et al., 1990). Northern source regions also include the West Greenland Current, southern Greenland, Hudson Strait, and coastal Labrador based on oxygen-isotope data, forming a long coastal current that extends from possibly as far north as Denmark Strait to Cape Hatteras in the south (Fairbanks, 1982; Chapman et al., 1986; Chapman and Beardsley, 1989). Thus, shelf waters over this large region are generally less saline and colder than the slope waters located further offshore (Bigelow and Sears, 1935; Wright and Parker, 1976; Beardsley, 1976) and are influenced by both the inshore and offshore branches of the Labrador Current, the western boundary current of the North Atlantic sub-polar gyre located within the Labrador Sea (Smith et al., 1937; Petrie and Anderson, 1983; Peterson, 1987; Greenberg and Petrie, 1988; Lazier and Wright, 1993; Drinkwater, 1996; Loder et al., 2001). The inshore branch of the Labrador Current flows south along the Labrador shelf and through Avalon Channel south of Newfoundland. The offshore branch of the Labrador Current bifurcates at the Flemish Cap with some flow turning eastward, while a second bifurcation occurs at the Tail of the Grand Banks, with a substantial fraction of the transport turning eastward to join the North Atlantic current extension of the Gulf Stream (Petrie and Anderson, 1983). Northeast shelf waters are also influenced by some of the strongest atmospheric forcing in the world (Thompson et al., 1988) with high variability and some recent extreme events (Chen et al., 2014), along with local river discharge. The largest source of freshwater river discharge is the St. Lawrence River, which connects to the northwestern corner of the Gulf of St. Lawrence (GSL). The large discharge from the St. Lawrence River eventually flows onto the Scotian Shelf, with the entire GSL contributing approximately 35% of the fresh water to the Scotian Shelf (Khatiwala et al., 1999).

The shelf break front (SBF) forms the boundary between shelf waters and the warmer and more saline slope waters located further offshore and is readily detectable year-round over a distance of greater than 2000 km, between the Tail of the Grand Banks (50° W) and Cape Hatteras (75° W) using satellite-derived sea surface temperature (SST) (Drinkwater et al., 1994; Bisagni et al., 2006). Given the competing effects of salinity and temperature on seawater density, the SBF is a partly density-compensated oceanographic front that slopes downward from its surface expression towards shore, exhibiting strong hydrographic seasonality (Flagg, 1977; Linder and Gawarkiewicz, 1998). Over more southern regions of this large shelf domain, seasonally-averaged changes of temperature, salinity, and density across the SBF are 5 °C, 2, and 0.5 kg $m^{-3}$, respectively, with maximum summer cross-frontal gradients and variance confined to subsurface waters (Garvine et al., 1988; Linder et al., 2006). Using an Ekman slab-layer model, Bisagni et al. (2006) show a clear annual cycle of the SBF surface position, with the SBF located offshore (onshore) during winter (summer) east of ~71° W. The annual cycle of the extreme western SBF segment (west of ~71° W) is 180° out of phase from the eastern segment due to the more southerly orientation of the local bathymetry. Hydrographic data from the Nantucket Shoals region (Linder and Gawarkiewicz, 1998) show the near-bottom SBF moving offshore during the February-April period, lagging the seasonal late-fall offshore movement of the surface outcrop of the SBF by about 4 months. Unrelated to Ekman forcing, an annual westward-propagating, seaward meander of the SBF occurs between November (at the Tail of the Grand Banks, 50° W) and April (south of Newfoundland, 56° W), corresponding to earlier upstream maximal seasonal transport of the Labrador Current during October near Hamilton Bank (Lazier and Wright, 1993; Bisagni et al., 2006). Inter-annual variability (IAV) of the SBF surface position over the same domain shows alternating periods of westward-propagating offshore (late 1970s, late 1980s, late 1990s) and onshore (early 1980s, early 1990s, early 2000s) annual mean SBF surface position anomalies, thus exhibiting a period of approximately 10 years (Bisagni et al., 2009), possibly related to shelf water volume variations. Moreover, at least from 1977 to 1999 within the Middle Atlantic Bight (MAB), IAV of the annual mean SBF position does appear related to the MAB-wide mean shelf water volume and salinity anomalies (Mountain, 2003), with offshore (onshore) SBF anomalies corresponding to periods with positive (negative) volume and negative (positive) salinity anomalies (Bisagni et al., 2009).

Long-term observational programs within Canadian shelf waters include hydrographic measurements by Canada's Department of Fisheries and Oceans (DFO) for the North Atlantic Fisheries Organization (NAFO) since the early 1970s (Doubleday, 1981) at 100–200 stations per survey, and the Atlantic Zone Monitoring Program (AZMP) from 1998-present, extending from the Newfoundland shelf to the western Scotian Shelf; including the St. Lawrence Estuary and the Gulf of St. Lawrence itself (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/index-eng.html). Long-term AZMP monitoring generally consists of 14 repeat (seasonal) hydrographic sections and 7 repeat stations, with some earlier stations (e.g., Station 27 near St. John's, Newfoundland) sampled since the 1970s. Some AZMP sections (e.g., Halifax section) were sampled on a semi-regular basis prior to 1998. Over southern U.S. waters, monitoring of the continental shelf largely began with the early work of Henry Bigelow and the ground-breaking studies within the Gulf of Maine (Bigelow, 1927). Later intensive broad-scale hydrographic surveys were conducted by the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA/NMFS) from the Gulf of Maine to the southern MAB and completed using stratified random sampling during spring and fall trawl survey program from the 1960s to present. From 1977 to 1987 the NOAA/NMFS Marine Resources, Monitoring, Assessment and Prediction (MARMAP) program surveyed the entire U.S. shelf region approximately seasonally at over 140 fixed station locations. The MARMAP program was followed by the U.S. Global Ocean Ecosystems Dynamics (GLOBEC) Northwest Atlantic Georges Bank program broad-scale surveys and process cruises (1995–1999) and the NOAA/NMFS Ecosystem Monitoring (EcoMon) program, extending these earlier shelf observational programs to present day.

Present work was motivated by the important role of fresh water for partly controlling vertical hydrographic structure, physical circulation patterns, physical, chemical, and biological processes, and indicating possible climate-related changes in the arctic and their impact within the “downstream” combined Canadian and U.S. Northeast Shelf Large Marine Ecosystem (NESLME). Importantly, salinity has been shown to be a valuable indicator of “regime shifts” (step-like changes) on Georges Bank, a limited region of the NESLME, where strong co-varying changes in both physical and biological properties (zooplankton assemblages and fish recruitment) have occurred, (e.g., Mountain and Kane (2010)). A numerical modeling study has shown that for Georges Bank, salinity is an important indicator influencing the phytoplankton bloom timing and magnitude on the Bank (Song et al., 2010) while observations within the Gulf of Maine show that salinity is the primary determinant of density stratification, dominating surface stratification during winter, spring and fall (Deese-Riordan, 2009). In addition, higher inflow of low salinity Scotian Shelf waters is associated with increased winter phytoplankton and zooplankton production in the Gulf of Maine (Durbin et al., 2003; Pershing et al., 2005), which can affect Georges Bank cod and haddock populations (Mountain and Kane, 2010). Further upstream on the