Gulf of Maine salinity variation and its correlation with upstream Scotian Shelf currents at seasonal and interannual time scales

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Abstract In the Gulf of Maine (GoM), a network of buoy hydrography measurements collected since 2001 provide a subsurface salinity time series showing a strong seasonal cycle and interannual variations that are both consistent with remote forcing of Gulf hydrography by upstream advection. These long-term mooring data are combined with satellite altimeter estimates of upper ocean current anomaly on the adjoining Scotian Shelf (SS) in a new attempt to use disparate regional observations as proxies to detect and evaluate remote forcing of water mass change inside the Gulf from 2002 to 2015. Focusing on buoys moored along the Maine coastal current (MCC), lagged cross correlations with upstream altimeter-derived SS current anomalies are found to be as high as 0.84 and explain 50–70% of variance in the MCC subsurface salinity data at both seasonal and interannual time scales. Significant MCC freshening in 2004–2005 and 2010–2011 follow SS velocity strengthening, while salting events in 2002–2004 and 2012–2015 are associated with relaxation of SS currents. Estimated time lags translate to advective SS inflow velocity estimates of $6 \pm 2$ cm/s that are consistent with past modeling and observational work. Investigation of wind stress control on SS velocity anomalies indicates that wind directions away from the along-shore can factor into flow modulation. Overall, the study findings are consistent with past freshwater flux observations and modeling examining southwest SS inflow to the GoM, provide a new empirical means to diagnose GoM hydrographic change, and point to one potential application of an altimeter measurement record that extends from 1992 into the future.

1. Introduction

There is significant recent focus on the identification and explanation of ecological, biochemical, and physiological effects of interannual variability in the Gulf of Maine (GoM) and surrounding waters including the Nova Scotian Shelf (SS) [Mountain, 2003; Pershing et al., 2010; Smith et al., 2001, 2012; Ji et al., 2008; Townsend et al., 2015]. Interest in GoM water mass variability is not new [Bigelow, 1924; Fournier et al., 1977; Petrie and Drinkwater, 1993; Loder et al., 2001] with prevailing reasons being the presence of extensive marine life and active fisheries. The ecosystem productivity is well known and attributed to the particular topography and bathymetry of the Gulf and adjoining shelf, access to nutrient-rich slope waters, and strong tidal and seasonal mixing [Bigelow, 1927]. What is relatively new is the decline in many marine species in the regional food web, the likelihood of arctic impacts, ocean warming, and biochemical changes, and the need to more fully understand and predict the impacts of these changes on present and future GoM ecosystems [Petrie and Drinkwater, 1993; Loder et al., 2001; Greene and Pershing, 2001; Wiebe et al., 2002; Durbin et al., 2003; Pershing et al., 2005; Mountain, 2004; Mountain and Kane, 2010; Greene et al., 2013; Runge et al., 2015]. Moreover, the Gulf lies within the greater Northwest Atlantic (NWA) shelf circulation and its southwestward flow from the Labrador Sea and Grand Banks, to the Gulf of St. Lawrence and Scotian Shelf, and then equatorward toward Cape Hatteras. Thus investigation of local and remote forcing impacts on internal Gulf circulation needs upstream information [Csanady, 1978; Csanady and Hamilton, 1988; Xue et al., 2000; Smith et al., 2001; Loder et al., 2003; Urrego-Blanco and Shen, 2012, 2014] and will also have implications for sites downstream [Chapman et al., 1986; Mountain, 2003; Mountain and Taylor, 1998].

The mean GoM circulation and that for the adjoining upstream Scotian Shelf have been well documented using both observational and numerical modeling approaches. We refer readers to Townsend et al. [2006] for a review of the Gulf of Maine, and Smith et al. [2001] for a review of the Scotian Shelf system.
and Smith and Schwing [1991] for review. Moreover, the topic of temporal change in GoM water masses and potential ramifications on biochemistry have been addressed from several perspectives and timescales. Long-term hydrographic sampling data along the coastal NWA region suggests that shelf-wide decadal scale variations in the temperature and salinity may be tied to modulation of upstream the Labrador Current transport as well as the North Atlantic Oscillation atmospheric pressure index [Loder et al., 2001; Greene et al., 2013; Han et al., 2014]. A primary concern here has been on the fairly substantial temperature changes associated with such regime shifts and their net impact on the ecosystem. In studies more narrowly focused on GoM basins, Georges Bank, and at shorter time scales, there has been considerable emphasis given to the complex shelf and slope water mass exchange that takes place via key GoM entry points [Smith et al., 2001, 2012; Townsend et al., 2015]. While there is some consensus that region-wide impacts are associated with remote forcing tied to upstream changes (e.g., Gulf of St. Lawrence, Labrador current), the evidence for a potential GoM hydrographic regime shift between the 1990s and the 2000s is not yet conclusive [Smith et al., 2012]. Furthermore, a case has been made for considerable local control at the interannual time scales including river freshwater inputs and wind forcing [Mountain and Manning, 1994; Li et al., 2014]. Finally, there is still substantial uncertainty in linking transport or hydrographic variation along the Scotian shelf to the hydrographic variation of the interior GoM, including along the somewhat distant Maine coastal current (MCC). Central limitations noted in these previous GoM-SS regional investigations involve the complexity of the overall coastal circulation combined with a lack of long-term observations having sufficient water column sampling and spatial coverage. This study attempts to exploit two observational elements of the regional long-term continuous sampling system that do exist here, satellite altimetry and the GoM buoy network, to explore new alternative approaches for diagnosing Gulf of Maine hydrographic change.

Logically, GoM water mass regime shift investigations largely focus on variability in inflows [Smith et al., 2012; Townsend et al., 2010]. The Gulf is a semi-enclosed marginal sea and receives its bulk of inflow from two specific pathways in the eastern side of Northeast Channel (NEC) and the shallower Northern Channel (NC) that lies between Browns Bank and Cape Sable (CS) off the Yarmouth Nova Scotia shelf (see Figure 1) [Smith et al., 2001; Hannah et al., 2001; Brickman et al., 2015]. As discussed most recently in Townsend et al. [2015], one key puzzle in diagnosing variable Gulf hydrography lies in the complexity of the sea-slope exchange within the NEC, which in a given year, or even month, can involve an inflow admixture of Atlantic slope water, Labrador slope water, Gulf Stream meanders, and Scotian Shelf water. NEC inflow and outflow is now known to be highly variable with depth [Ramp et al., 1985; Smith et al., 2001, 2012] as well as across and along the NEC, making it a difficult system to monitor and evaluate. Another difficulty in diagnosing the GoM-Atlantic shelf exchange is the frequent reliance on water mass assessment using observations in the three deeper (100–300 m) basins of the Gulf of Maine. Indeed, deeper basin observations below 100 m can inform on part of the water mass exchange, but may largely neglect the impact of the SS inflow that can travel north and eastward of these basins and advects counterclockwise (CCW) along to the MCC (see Figure 1).

The interplay between SS inflow via the NEC versus the relatively shallow coastal Northern Channel off the Cape Sable shelf is a key remaining issue. Both Smith et al. [2012] and Townsend et al. [2015] suggest the likelihood of net balance and feedbacks between these inflows; increased Cape Sable SS inflow is postulated to inhibit deepwater NEC inflow. Their work also suggests new emphasis be placed on detecting and understanding variability in this northern channel inflow pathway at interannual to decadal scales. These papers further propose a hypothesis that a GoM water mass shift has occurred in the last 10–15 years due to a substantial SS water transport increase. Such a result should reflect itself in observed freshwater increases and nutrient shifts, and with potential impacts on stocks such as zooplankton [Runge et al., 2015].

An overall goal of this study is to develop further insight into the response of the interior Gulf of Maine subsurface salinity to variations in the SS water inflow. The investigation will provide observations of GoM hydrographic change at seasonal-to-interannual time scales by focusing on the MCC utilizing long-term hourly salinity measurements (2001–2015) from six separate GoM moorings (Figure 1). Salinity change observed within the MCC and along to the mid-Atlantic Bight has been addressed before [Mountain, 1991; Mountain and Manning, 1994; Geyer et al., 2004; Churchill et al., 2005; Pettigrew et al., 2005], but often with an emphasis on local river inputs and salinity and on the seasonal surface plumes that reside atop this coastal current during the spring freshet. The investigation in this paper focuses on subsurface salinity ($S_{50}$)
observed at 50 m depth, well below local river plumes and below the seasonal mixed layer, and follows on from recent studies of the remote and advective control of the circulation on the Scotian Shelf and along to the GoM and MCC - forcing that likely exists at seasonal to interannual scales [Smith, 1989; Smith et al., 2001; Ji et al., 2008; Deese-Riordan, 2009; Urrego-Blanco and Sheng, 2014; Li et al., 2014; Brickman et al., 2015].

The key study idea is to evaluate the strength of the correlation between two available long-term observational freshwater flux proxies that straddle the northern channel inflow. In particular, the upstream proxy is taken as the southwest Scotian shelf geostrophic velocity attained via altimetry and the internal GoM proxy is buoy-observed S50 along the core MCC. We will provide observational evidence supporting the selection of these freshwater flux proxies (see Section 2.3). An additional issue tied to SS inflow variation is the question of remote versus local control of the transport. Li et al. [2014] presented evidence supporting the hypothesis that local wind stress variation factors strongly into the interannual control of SS velocities and resulting volume transport into the Gulf of Maine. Their work suggests that along-shelf wind variation may effectively serve as a inflow control valve. Our study will use long-term wind stress data sets to further investigate this idea and to assess the impact of wind directionality on SS currents at different time scales.

The paper is structured as follows. Section 2 describes the long-term observational data sets and analysis methods. Section 3 examines temporal and spatial variation of buoy-measured subsurface salinity and altimeter-derived along-shelf upper-ocean geostrophic current anomalies in the SS-GoM shelf system. Specific attention is paid to relationships between along-shelf SS current and interior GoM subsurface salinity changes at seasonal and interannual scales. Section 4 provides discussion and also includes an assessment of the impact of local wind forcing on SS along-shelf flow. Conclusions are drawn in Section 5.
2. Data and Methods

2.1. In Situ and Satellite Altimeter Data

Hydrographic data come from met-ocean measurement buoys deployed by the University of Maine as part of the Northeast Regional Association of Coastal Ocean Observing Systems (NERACOOS, http://www.neracoos.org/). These GoM buoys collect and report data at hourly and shorter intervals and are operated almost continuously, many from 2001 to present, and with limited data dropouts and few data quality issues. Specific stations for this study include those denoted as buoy L, I, E, and B that are moored at the 60–70 m, the latter three along the nominally CCW inner Gulf MCC (see Figure 1). Buoys M and N are sited in the deeper Jordan Basin and Georges Basin/Northeast Channel, respectively. Each buoy has temperature and salinity sensors at depths of 1, 18, and 50 m as well as horizontal currents measured vertically through the water column using Acoustic Doppler Current Profilers (ADCP). Buoys M and N also have measurements at depths that extend to 200–300 m.

Supporting hourly wind observations for the Scotian shelf region come from the location: Yarmouth, Canada. The shore-based site is operated by Environment Canada. Data were acquired via the Atlantic Zone Monitoring Program (AZMP) website (http://www.meds-sdmn.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/index-eng.html). Hourly wind observations are available from 1953 to 2013. Normal 10 m wind velocity data were then used to calculate surface wind stress in terms of the formulation of Large and Pond [1981].

The satellite altimeter data are from cycles 1–364, 1–260, and 1–255 of the TOPEX, Jason-1, and Jason-2 geophysical data records (GDR), respectively. These orbit cycles correspond to periods of October 1992 to August 2002, January 2002 to January 2009, and July 2008-present. Together they provide a nearly continuous sampling of the same satellite tracks from 1992 to 2015. These altimeters have collected sea surface height anomaly (SSHA) measurements in this same 10 day repeat orbit along the ascending (SW-NE) and descending (NW-SE) ground tracks. Along-track SSHA data with spatial sampling resolution of nearly 6 km (1 Hz) are processed and filtered to provide optimal data quality following the coastal data assessment scheme outlined by Feng and Vandemark [2011], and the altimeter data for each satellite are taken from the Radar Altimeter Database System (RADS) [Scharroo, 2009]. Latest-generation environmental corrections have been applied to the 1 Hz altimeter sea level data including the wet troposphere delay measured by the microwave radiometers (TMR, JMR and AMR for TOPEX, Jason-1, and Jason-2, respectively), ocean and solid tides by GOT4.8, dry troposphere via the ECMWF model, high frequency ocean response by MOG2D model, ionosphere by smoothed dual-frequency correction, sea state bias by nonparametric estimates, and the DUT2010 mean sea surface.

This study focuses on three ground tracks, i.e., T0100, T0024, and T0202, and the 10 day time interval SSHA time series collected near the shelf-break front that extends from the southwest Scotian shelf, southward to the Mid-Atlantic Bight (40 N and southward). Highlighted boxes on the satellite tracks (Figure 1) represent the location of the altimeter SSHA measurements used to estimate the upper ocean geostrophic velocity along the shelf break front, and normal to the satellite ground track [e.g., Strub et al., 1997]. For these tracks, the direction of estimated cross track velocity aligns closely with the predominant southwest (nearly along-shelf) flow associated with both Scotian shelf and Labrador currents [Han, 2007]. Track 100 provides an SSHA transect nearly perpendicular to the local isobaths on the southwest Nova Scotian Shelf.

2.2. Satellite-Derived Geostrophic Current and In Situ Assessment

Satellite altimeter cross-track geostrophic velocity anomalies ($V_g$) are calculated from the along-track gradient of sea surface height using a centered finite difference taken across 11 samples (i.e., roughly 60 km) along each track. The resulting 6 km $V_g$ product is then subjected to a three-point running mean spatial filter to attenuate high spatial frequency variability along the satellite track [Strub et al., 1997; Feng and Vandemark, 2011]. Note that the resulting altimeter $V_g$ time series are derived from SSHA and thus actually represent an estimate of the modulation (i.e., anomaly), in the mean geostrophic flow. The term $V_g$ used going forward, represents the cross-track geostrophic current anomaly. There are several sources of potential error in altimeter-estimated $V_g$, including unresolved spatial heterogeneity along a track and significant under-sampling in time due to the 10 day repeat orbit. Altimeter $V_g$ data on track 024 have been shown to compare favorably to appropriately filtered in situ current measurements at buoy N [Feng and Vandemark, 2011]. Buoy N is the best available GoM site for a direct $V_g$ validation with insitu measurements even though the cross NEC current is relatively weak and the upper-ocean flow around buoy N is known to be complex.
To support this study, an extended data set of altimeter-derived $V_g$ normal to track 024 and within 20 km of buoy N is compared to ADCP velocity data from 2004 to 2015. The buoy data are processed to remove the tides and the mean currents and the resulting current anomalies are rotated to the altimeter $V_g$ projection and then subsampled to match the 10 day sampling of the altimeter. Results from this direct comparison, after applying a 70 day running mean to both altimeter $V_g$ and buoy ADCP time series, are shown in Figure 2. The RMSE is 3.2 cm/s and the correlation coefficient is about 0.64. As noted, and consistent with Feng and Vandemark [2011], best agreement with VADCP at this site is found when averaging the ADCP currents (4 m vertical sample intervals) between 32 and 48 m (Table 1). This indicates that currents at these depths best represent the geostrophic cross channel flow. Comparison statistics provided in Table 1 provide results for this depth-mean VADCP from 32 to 48 m as well as those at specific upper ocean depths. While the matchups are in reasonable agreement, we attribute remaining disagreement to ageostrophy inherent in VADCP [Strub et al., 1997] as well as to the 20 km distance from buoy N to track 024 that may lead to a collocation error in events with persistent variability in the cross channel flow.

### Table 1. Statistics of (R) Correlation Coefficient, RMSE (cm/s), and (N) Number of Observations Between Jason 1 and Jason 2 Altimeter-Derived Surface Cross-Track Geostrophic Current Anomaly $V_g$ at Track 24 and the In Situ Measured Current at Buoy N at Depth-Average (32–48 m), 24, 32, 40, 48 and 56 m With Different Low Pass Filters

<table>
<thead>
<tr>
<th>Depth (m)</th>
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<th>RMSE (cm/s)</th>
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<td>318</td>
</tr>
<tr>
<td>32</td>
<td>0.56</td>
<td>4.52</td>
<td>309</td>
</tr>
<tr>
<td>30 day LP</td>
<td>0.56</td>
<td>4.52</td>
<td>309</td>
</tr>
<tr>
<td>70 day LP</td>
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<td>318</td>
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<td>70 day LP</td>
<td>0.64</td>
<td>3.55</td>
<td>301</td>
</tr>
<tr>
<td>48</td>
<td>0.40</td>
<td>7.37</td>
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<td>301</td>
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<tr>
<td>56</td>
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<tr>
<td>30 day LP</td>
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<tr>
<td>70 day LP</td>
<td>0.63</td>
<td>3.02</td>
<td>301</td>
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</tbody>
</table>

*Raw data, and 30-day and 70-day running mean low-passed data.
et al., 1986; Smith, 1983; Smith et al., 2001; Smith, 1989; Urengo-Blanco and Sheng, 2014], (ii) \( Q_s \) on the southwest Scotian shelf is correlated with \( Q_S \) in the GoM MCC at seasonal to interannual time scales, and (iii) SS geostrophic velocity modulation and GoM subsurface salinity time series are viable surrogates for temporal variation in these two distinct but correlated fluxes.

Results to follow will evaluate the consistency of the first two assumptions. To support the third, we note that observed annual cycle of altimetric current variation on the southwest SS just upstream of Cape Sable (to be shown in Section 3.2) is consistent with the results from investigation of inflow near Cape Sable by Smith et al. [2001]. In that study, depth-integrated volume and freshwater transport time series, \( Q_v(t) \) and \( Q_s(t) \), were estimated based on the depth-averaged profiles of measured along-shelf current \( V(z) \) and salinity \( S(z) \) over a given water depth \( H \) (\( H_1-H_2 \)), as below

\[
Q_v(t) = \int_{H_1}^{H_2} V(z)dz \approx \sum_{i=1}^{N} V_i \Delta Z_i \tag{1}
\]

\[
Q_s(t) = \frac{1}{S_0} \int_{H_1}^{H_2} V(z)(S_0-S)dz \approx Q_v(t) - \frac{1}{S_0} \sum_{i=1}^{N} V_i S_i \Delta Z_i \tag{2}
\]

Note that \( Q_v(t) \) and \( Q_s(t) \) are differential transport estimates to be integrated laterally over a section to provide total transports. Smith et al. [1989, 2001] provided seasonally-resolved estimates of \( Q_v(t) \) and \( Q_s(t) \) estimates at a station off the CS shelf (along the 100 m isobath) using multiyear current and hydrography measurements. The annual cycles of subsurface along-shelf currents and salinities, as well as \( Q_v \) and \( Q_s \), all reveal consistent temporal variation pattern, with maximum and minimum inflow in early winter (Jan/Feb) and in early fall (Aug/Sep). The observed along-shelf current and \( Q_v \) variations are in phase with 50 m-salinity and \( Q_s \), [see Smith et al., 2001, Figure 3]. The strong self-consistency suggests that longer-term measurement record of either the time variable subsurface salinity or along-shelf currents can serve as a surrogate for freshwater flux \( Q_s \). As a further check, salinity data collected biweekly from 1999 to 2015 at the Halifax station (H52 hydrography, 44.27N, 63.32W), upstream from Cape Sable (http://www.meds-sdmn.dfo-mpo.gc.ca/isd-gdsi/azmp-pmza/hydro/station/multiple-eng.asp) were used to calculate the average annual cycle of subsurface salinity. Results reveal Halifax salinity variation (winter minimum of 31.4 psu, summer maximum of 32.4 psu) nearly in phase with Cape Sable salinity, \( Q_v \), and \( Q_s \), time series as well as altimeter-derived geostrophic velocity anomaly time series from Track 100. Overall, it appears viable to use the velocity anomalies (available 1992-present) as a proxy for \( Q_v \) near to Cape Sable.

Internal to the Gulf of Maine, the spatial variations in sea level anomaly are small and thus satellite altimeter data are of limited use for this application. Rather, the \( Q_v \) proxy uses \textit{in situ} salinity measurements collected in the Gulf of Maine and foremost from buoys (I, E, and B) within the MCC, moored inside of the 100-m isobath. This is further limited to use of the subsurface salinity measurements at 50 m depth (\( S_{50} \)). Geyer et al. [2004] indicated that salinity below 30 m in the MCC, at least west of buoy E, should be weakly impacted by freshwater from buoyant coastal river plumes that form often during the local spring freshet, and that hydrography variation at 50 m might reflect advection impact due to remote upstream GoM inflow. NERACOOS buoy time series of temperature, salinity and currents at stations N, L, M, I, E, and B (Figure 1) were evaluated from the surface to 70 m from 2001 to 2015 with an objective toward identification of covariance between the sites at monthly to seasonal time scales. Our findings (not shown) were that both temperature and current data exhibit extensive local influence due to both horizontal and vertical mixing and seasonal heat flux. This was especially evident above 20 m depth but also down to the bottom 60–70 m [Pettigrew et al., 2005].

As an added check, buoy estimates (at I and E) of the annual cycle of \( Q_v \) and \( Q_s \) were made using along-shelf current profile \( V(z) \) at depths from 30 m to 70 m and using subsurface salinity \( S_{50} \) at 50 m following Eqs. (1) and (2). Figure 3 displays the annual-cycle climatology of volume transport \( Q_v \) (Figure 3a) and subsurface salinity \( S_{50} \) as well as freshwater transport \( Q_s \) (Figure 3b) at buoy E. Note that negative \( Q_v \) and \( Q_s \) represent southwest transports approximately along the local isobath. The buoy-derived \( Q_v \) and \( Q_s \) and \( S_{50} \) time series at buoy E are highly correlated and nearly in phase. However, \( S_{50} \) and \( Q_s \) time series are closely correlated while this is less so between \( S_{50} \) and \( Q_v \), especially at buoy I (not shown). This again implies more local processes likely influencing currents, and yet a viable \( Q_v \) proxy in the subsurface salinity \( S_{50} \) data for the MCC.
In all, these consistency checks, previously published studies, and the forthcoming data analysis combine to provide evidence supporting the use of these two freshwater flux proxies.

2.4. Low-Passed Filters and Correlation Analysis
All time series in this study are processed using 70 day and 450 day running mean low-passed (LP) filters for the respective evaluation of seasonal and interannual variability. The former is set to sufficiently attenuate high frequency aliasing, such as the tides and high frequency barotropic sea surface impacts. Though a running mean low pass filter is suboptimal in removing high frequency content, no significant differences in results from statistical analysis are observed when replacing it with other advanced filters. Moreover, such running mean low-passed filter avoids loss of temporal resolution prior to statistics analyses (see appendices in Strub et al. [1997] and Li et al. [2014]). In the case of subsurface salinity $S_{50}$ and wind stress $\tau$, anomaly time series are calculated after the removal of the monthly climatology developed over the extent of the available time series. This is more than 60 years for the wind data and from 3 to 14 years for the buoy salinity data sets.

Note that the original observations of $S_{50}$ (and $\tau$), and $V_{9100}$ are in hourly and 10 day time resolutions, respectively. In order to perform cross-correlation analyses using time series with different resolutions, the selected low-passed filter (70 or 450 day running mean) is first applied to the both time series of $S_{50}$ (or $\tau$) and $V_{9100}$. The resultant LP time series of $S_{50}$ (or $\tau$) with hourly time resolution is then subsampled to match the 10 day resolution in altimeter velocity $V_{9100}$. Therefore, the effective number of observations and degree of freedom based on coarser time resolution time series are used for estimating p-values and the 95% significance level in the correlation analyses.

3. Results

3.1. Subsurface Salinity Variability at Annual and Interannual Scales
GoM salinity undergoes significant annual and inter-annual variability in both surface and deep waters [Mountain and Manning, 1994; Taylor and Mountain, 2009]. The salinity as a whole is largely controlled by...
Here we present the mean seasonal cycle and inter-annual variability of subsurface salinity $S_{50}$ at the depth of 50 m for the period from 2001 to 2014. Figure 4 shows the 70-day running mean time series of $S_{50}$ observed at buoys N (NEC), L, M (Jordan’s Basin), I, E, and B. Salinity $S_{50}$ across most of the Gulf ranges from 31.6 to 33.5 psu in the seasonal cycle, with a peak-to-peak variation of about 1.0 psu for any given site. Generally, the various $S_{50}$ time series are coherent with respect to each other, particularly so for the coastal buoys L, I, E and B that extend from the east to the west along the MCC (Figures 1, 4b, 4d, 4e, and 4f). $S_{50}$ at deeper basin buoys N and M (Figures 4a and 4c) appear less periodic and less energetic in their seasonal variability compared to the coastal sites. The standard deviations of salinity $S_{50}$ time series for all sites were also calculated to quantify the characteristic $S_{50}$ variability (see Table 2). The buoy L time period is significantly shorter, leading to larger uncertainty in statistics and the computed anomalies.

### 3.1.1. Mean Seasonal Cycle

Climatological daily means of buoy-observed $S_{50}$ records are provided in Figure 5a. A periodic annual cycle for $S_{50}$ is much more apparent for the coastal sites L, I, E, and B, than for the deeper basin buoys M and N. The timing and magnitude of freshening depends on location. On average, seasonal freshening at 50 m usually happens from October to May on the southwest Scotian

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**Table 2.** Standard Deviation (in psu) of Buoy Observed Low Passed and Anomaly (Monthly Climatologic Means Removed) Subsurface Salinity $S_{50}$

<table>
<thead>
<tr>
<th>Buoy ID</th>
<th>Seasonal</th>
<th>Anomaly</th>
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<tbody>
<tr>
<td>N</td>
<td>0.43</td>
<td>0.34</td>
</tr>
<tr>
<td>L</td>
<td>0.43</td>
<td>0.31</td>
</tr>
<tr>
<td>M</td>
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<td>0.29</td>
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<tr>
<td>I</td>
<td>0.38</td>
<td>0.23</td>
</tr>
<tr>
<td>E</td>
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<td>0.27</td>
</tr>
<tr>
<td>B</td>
<td>0.38</td>
<td>0.24</td>
</tr>
</tbody>
</table>

*aBased on 70-day running mean low passed time series.

*bBased on 70-day running mean low passed monthly anomaly time series (i.e., monthly mean removed, representing inter-annual variability).
Shelf (representative of buoy L), from November to June on the eastern GoM shelf (representative of buoy I), and from January to July on the western GoM shelf (representative of buoys E and B), as shown in Figure 5a. Seasonal salting starts in early summer toward the maxima in fall or late fall, and can last approximately from four to 7 months depending on location; the shortest salting period is in the southwest SS and the longest in the western GoM. The $S_{50}$ minimum occurs earlier in the east (buoy L) than in the west (buoy B). The lowest salinity is observed at buoy B on the western end of the MCC. This notable feature is expected, and attributed to the fact that there is substantial local river runoff along the Maine coast in the spring to summer [e.g., Geyer et al., 2004] with some vertical mixing events to impact $S_{50}$, while there is no similar local freshwater source near buoy L.

Buoy N represents a unique and key monitoring site in the eastern NEC at the mouth of the Gulf of Maine (Figure 1). Data there display the least organized annual cycle of subsurface salinity $S_{50}$ among these buoy locations under consideration. As well recognized, the circulation variation and thus water mass evolution in the NEC is considerably more complex than along the MCC sites [Brown and Irish, 1993; Smith et al., 2012; Townsend et al., 2015].

Qualitatively, the observed time lags in $S_{50}$ between sites L, I, E, and B in Figure 5a may be used to infer freshwater propagation from east to west along the GoM coastal shelf. A simple estimate for the average-

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Figure 5. Daily climatology of (a) salinity $S_{50}$ and (b) temperature $T_{50}$ measured at a depth of 50 m for each buoy (see buoy locations in Figure 1) using all available hourly data within the time periods indicated in Figure 3.
Such a characteristic is particularly apparent in subsurface layer (S50 and T50) but not in the surface in our
reported that salinity cycles are lagged around the GoM shelf but temperature cycles are nearly in phase.

As noted earlier, the indication of advection using S50 within the coastal GoM is not so apparent in the sub-
surface temperature data. To illustrate, climatological daily means of buoy-observed subsurface tempera-
ture T50 at 50 m depth for the same sites are provided in Figure 5b. T50 records show no significant time
phase lags between buoy locations. Studies by Mountain and Manning [1994] and Deese-Riordan [2009] also
reported that salinity cycles are lagged around the GoM shelf but temperature cycles are nearly in phase.

Such a characteristic is particularly apparent in subsurface layer (S50 and T50) but not in the surface in our
analysis (not shown). Moreover, the annual minima and maxima are clearly shifted away from the corre-
sponding epochs in S50. This apparent difference between the T50 and S50 seasonal cycles is most likely due
to a strong difference between vertical temperature and salinity mixing within each year. Over most of
the GoM region and annual cycle, the vertical gradient in temperature at the base of the mixed layer is
much stronger than for salinity, particularly on the western GoM shelf (not shown). Based on 1-D vertical
transport equation for heat and salt balances, the vertical heat mixing is much efficient than the vertical salt
mixing. Therefore, local heating impact on subsurface T50 dominates the advection influence on T50.

### 3.1.2. Interannual Variation

The subsurface salinity S50 (observed at 50 m depth) anomaly time series for these same buoys with 70 day
filtering is provided in Figure 6 with standard deviations given in Table 2. Compared to the annual cycle of
S50, standard deviations of anomalies are lower at most of the buoy sites, ranging from 0.23 to 0.34 psu.
Inter-annual variability is apparent in Figure 6, revealing significant low-frequency subseasonal signals at
each site. The anomaly magnitudes at most locations are similar with the exception being buoy N. The
observed temporal patterns of S50 appear coherent amongst buoy locations to a large extent, this observa-
tion being perhaps the most striking result seen in Figure 6. The data across GoM sites show positive anom-
aliesthe mid-2004 to the end of 2005; this for all the coastal shelf buoys as well as the Jordan basin
buoy M. A second fresh period (negative anomalies) appeared between 2010 and 2012. The S50
anomalies for buoy N correlate with some of these features but lack similar coherency with the other sites.
For instance, its freshness in 2004–2005 is much less significant than those in other sites, and S50 in 2007
shows a strong negative anomaly opposite to the other locations. All buoys indicate a strong salting is pre-
sent from 2012 to 2015 with the largest anomaly at buoy N. The timing of the anomalies and their magni-
tude do differ slightly between locations but details are also smeared to some extent by the 70 day
smoothing.

### 3.2. Along-Shelf Geostrophic Velocity Variations

This section details altimeter-derived current information obtained at the shelf break locations outside of
the Gulf of Maine noted in Figure 1. Recall that altimeter-derived currents (Vg) are estimates of upper ocean
geostrophic anomalies associated with the slope of altimeter along-track SSHA, and a measure of geo-

The long-term record of altimeter-inferred Vg variability in the equatorward along shelf flow adjoining the
Gulf of Maine is shown in Figure 7 for tracks 100, 024, and 202 (Figure 1) from top to bottom, respectively.
These time series were calculated by averaging Vg estimates across the shelf-edge (100–1000 m isobaths)
over the period from 1992 to 2015 with 10 day sampling resolution. The data reveal prominent annual
and interannual Vg variation. A seasonal cycle in Vg at each site is somewhat apparent, largest downstream
in winter (negative anomalies) and weakest in summer (positive anomalies). The velocity anomalies magni-
tude varies from ±10 cm/s for these tracks and there is a reasonable level of temporal coherency amongst
the three locations for several of the time periods with larger excursions (e.g., 1998, 2002, 2005). It is also
apparent that the high-frequency variation is more energetic in Vg202 than for the other two sites. The rea-
son may be because the Vg202 estimates for track 202 are centered on the southern edge of the shallow
George’s Bank where additional processes are thought to impact the cross-shore sea surface slope.
measured by altimetry. For instance, significant interactions exist between Gulf Stream warm-core rings and the shelf break front influences [Brooks, 1987; Ryan et al., 2001]. Residual topographically rectified tidal current variation exist there as well [Lynch and Naimie, 1993; Chen et al., 2001].

To quantify the coherency, a correlation analysis for altimeter current \( V_g \) time series between track 100 and each of the other tracks (at zero lag) was conducted, given in Table 3. As shown, there are positive correlations with both the seasonal (70 day running mean filter) and interannual (450 day running mean filter) time series. For seasonal scales, the derived correlation coefficients are 0.60 and 0.47 between \( V_{g100} \) and \( V_{g24} \) and \( V_{g202} \), respectively. For the interannual scales the corresponding correlation coefficients are 0.64 and 0.47.

Figure 8 shows an estimate of the climatological SS current \( V_{g100} \) for the full shelf taken from track 100, as derived from the entire 10 day time series between 1992 and 2015. Negative (positive) \( V_{g100} \) represents southwest (northwest) velocity anomalies, essentially providing the annual cycle for along shelf current modulation at the shelf edge front. Peak-to-peak variation is roughly 4 cm/s with clear equatorward (down-shelf) maximum near day 50 and minimum (relaxation) at day 220. Long-term observations indicate this variation is anti-correlated with GoM \( S_{50} \). This is consistent with the expected advection of Scotian Shelf inflow to the GoM [Smith, 1989]. To illustrate, the climatological \( S_{50} \) results of buoy B from Figure 5 are superimposed in Figure 8 where one observes the freshest western GoM subsurface water occurring 115–125 days after the upstream SS \( V_{g100} \) maximum.

Given the study interest in investigating connections between along-shelf current \( V_g \) on the Scotian shelf and the interior GoM, specific attention is next given to the across-shelf characteristics in \( V_{g100} \) that can be resolved by fine scale (order 20–40 km) [Strub et al., 1997] evaluation of data on altimeter track 100 from seaward of the shelf.
break onto the Scotian shelf and to within 20 km of the coastline. A time-latitude plot of the 70 day running mean \( V_{g100} \) is displayed in Figure 9. As noted in Figure 1, the Scotian shelf current is known to have inshore and shelf break branches that are thought to be distinct, but well-correlated and the lower panels in Figure 8 provide an indication that \( V_g \) averaged for data on the shelf are indeed coherent with those taken only at the shelf edge. Data in Figure 9 do however indicate a level of across-shelf \( V_{g100} \) variability with the shelf-edge flow often exhibiting larger perturbations than seen on the shelf. An analysis of the time lagged cross correlation between the shelf and the shelf-edge flows gives a maximum correlation of about 0.65 with a phase lag of about 20 days where the shelf flow leads. To further illustrate the interannual variability in the altimeter current derived from track 100, residuals of \( V_{g100} \) (monthly means removed) are calculated and shown in Figure 10 for the two segments. Figures 10a and 10b display residual time series of current \( V_{g100} \) on the shelf edge and on the shelf, respectively. Interannual

\[
\begin{array}{|c|c|c|}
\hline
\text{Table 3. Correlation Between Low Pass (LP) Filtered Altimeter-Derived Surface Cross-Track } V_{g100} \text{ at Track 100 Against } V_{g202} \text{ and } V_{g024} \text{ at Tracks 24 and 202 at the Shelf Edge (100–1000 m) (See Figure 1)} & \\
\hline
 & \text{Correlation Coefficients}\text{a} & \text{Number of Observations} \\
\hline
V_{g100} \text{ versus } V_{g202} & 0.47^b/0.47^c & 857 \\
V_{g100} \text{ versus } V_{g024} & 0.60^b/0.64^c & 857 \\
\hline
\text{aAll correlation coefficients reported here are significant at } p < 0.001 \\
\text{bBased on 70 day running mean low passed } V_g \text{ time series} \\
\text{cBased on 450 day running mean low passed residual } V_g \text{ time series.}
\end{array}
\]

3.3. Relation of GoM Subsurface Salinity Variability to the SS Inflow

In the previous sections, we have described the characterization of the temporal and spatial variability in both the GoM buoy-measured salinity $S_{50}$ and the altimeter-derived along-shelf geostrophic currents on Figure 8.

**Figure 8.** Annual climatology of salinity $S_{50}$ measured at buoy B and altimeter-based geostrophic current anomaly $V_{g100}$ measured on track 100 averaged across the self and shelf break segments (Figure 1). Negative (positive) $V_{g100}$ approximately represents southwest (northwest) flow anomalies.

**Figure 9.** (top) Time-latitude representation of altimeter-based surface current anomaly ($V_x$) computed for locations along track 100 from offshore (lowest latitude) and onto the shelf (see Figure 1). Note negative/positive values in $V_x$ represent relative increase/decrease in mean downstream flow. Data are smoothed with a 70 day moving average low-passed filter. The portions of shelf and shelf edge segments are highlighted. (bottom) The three time series of $V_x$ averaged at the shelf edge, at the shelf, and for the full shelf (combined) from top to bottom.
the Scotian Shelf separately. The SS-GoM system in the NWA shelf region is an advection-dominated system as well recognized [Smith, 1989; Urrego-Blanco and Sheng, 2014]. Freshening events in the interior GoM are thought to coincide with the fresh and cold SSW inflow in the southwest Scotian Shelf, subsequent anti-clockwise advection along the MCC pathway, as well as penetration into the central Gulf including Jordan Basin.

As discussed earlier, altimeter-derived \( V_{g100} \) and in the interior GoM \( S_{50} \) is treated as proxies for freshwater flux in the southwest SS and advection-impact along the MCC, respectively. Here we examine the relationship of long-term \( S_{50} \) variation in the interior GoM with respect to the upstream SS current \( V_{g100} \) modulation at both seasonal and interannual time scales.

Figure 11 shows the 70 day low-passed time series of salinity \( S_{50} \) (left y-axis) at selected buoys (L, M, I, and B) aligned from east to west in the GoM and the altimeter along-shelf flow \( V_{g100} \) (right y-axis) for track 100. Note that a full shelf estimate is used for \( V_{g100} \) going forward in the analyses based on the overall coherence seen in Figures 8 and 9. The results to be presented do not change substantially if calculated using only shelf edge or near coast shelf \( V_{g} \) estimates on track 100.

The \( V_{g} \) time series have been offset in time using the time lag of maximum cross correlation (\( V_{g} \) leads \( S_{50} \)) in Figure 11. In general, the two independent observations exhibit statistically significant correlation between the GOM-interior salinity \( S_{50} \) and the altimeter-based SS \( V_{g100} \) at the seasonal scales. The
maximum correlation coefficients range from 0.55 to 0.81 (Table 4) at the seasonal time scale. Higher correlations are observed for the coastal buoys (B, E, I and L) than for the deeper basin buoys (N and M) (Figure 11 and Table 4). The highest and lowest correlations are 0.81 and 0.55 for buoy L and buoy N, respectively.

This observational result is not wholly unexpected. Given the proximity of buoy L to Cape Sable and the SS, one anticipates some reflection of the coastal current variability seen on the southwest Scotia shelf. Conversely at buoy N (NEC), water mass characteristics can be influenced not only by the lower salinity water from SS water but also by several other water masses from different depths [Townsend et al., 2015].

Moreover, note that the time lags representing maximum correlations are dependent on buoy locations, i.e., their distance from observations taken on altimeter track 100. For the coastal buoys, the time lags range from the shortest being 40 days at buoy L to the longest being 120 days at buoy B. Between these two buoys the other time lags exhibit a consistent phase increment that accords with down-coast advection and one generally observes higher to lower correlation values as distance increases. For buoy E in the central MCC, its correlation (0.69) is slightly lower than buoys B and I for the seasonal scale. This is likely attributed to the fact that local river runoff contribution to S50 is more significant at buoy E given its location slightly downstream of the Penobscot River mouth and its large seasonal surface freshwater input at that site.

Qualitatively, buoy I results in Figure 11 are perhaps most striking. Correlation in each year between shelf-averaged \( V_{S100} \) and the distant GoM MCC S50 indicate a strong connection, with the amplitude, phase, and
temporal duration of seasonal variations in shelf currents apparently leading $S_{50}$ by roughly 80 days over the period 2002–2015. Relaxation is associated with increased salinity and vice versa.

To focus on covariance at interannual time scales, a similar analysis is performed after creation of anomaly time series with a 450 day running mean applied to these residuals. Results are given in Figure 12 and Table 4. Again, statistically significant high correlations appear between the GOM-interior salinity $S_{50}$ anomaly and the SS inflow $V_{g100}$ residuals in the inter-annual time scale. The maximum correlation coefficients range from 0.62 to 0.84 (Table 4). Similarly, higher correlations appear for the buoys along the GoM coast than for the deeper basin buoys. The highest and lowest correlations are 0.84 and 0.62 for buoys L and N, respectively. For the Maine coastal shelf buoys, the time lags range from the shortest length of 30 days at buoy L and the longest of 140 days at buoy B between which the time lags exhibit a consistent phase incremental shift from the eastern to the western GoM coast.

Results from analyses at seasonal (70 day filtered) and interannual (450 day filtered) time series are highly consistent. One minor discrepancy is in the computed time lag of maximum correlation with values being slightly longer in the interannual analyses than those of the time series with the seasonal signals included.

### 4. Discussions

#### 4.1. A Means to Relate Scotian Shelf Inflow to Variation in GoM Bulk Water Properties

The recent observations and discussion of water mass mixing in the Gulf of Maine given in Townsend et al. [2015] help to frame discussion of the present findings. The focus of that study was on NERACOOS buoy N and M mooring data at depths at and below 100 m and then deducing variable inflow to the Gulf from slope waters and the shallower Scotian Shelf waters (SSW) via T-S analyses. The authors observed significant episodicity at monthly to seasonal time scales as well as clear inter-annual variation in salinity within Jordan basin. A key conclusion from that study was that observed episodic freshening of the deeper basin waters likely comes from increased SSW, and a realization that resolving SSW inflow variability is of similar or greater import than resolving slope water (e.g., Labrador versus Warm Slope water) variations when investigating bulk water mass change in the Gulf of Maine. Approaches to characterizing upstream inflows before they enter the Gulf were recommended in part to help diagnose what are presently unpredictable variations at key sites such as the NEC [Smith et al., 2012]. Results from our present study appear to provide relevant information in several respects.

First, with a focus on the circulation around the Gulf edge rather than the interior and NEC, the mean $S_{50}$ variation within a year (Figure 5) amongst the coastal buoys show a progressive seasonal cycle that is consistent with a general cyclonic advection. Both the local minima and maxima at each buoy indicate a progression around the GoM from nearby Cape Sable (i.e., buoy L) to the western buoy B site. The average min-to-max $S_{50}$ change is about 0.8 psu. These results are consistent with the general understanding that relatively fresh coastal SSW enters the eastern Gulf of Maine at depths to 100 m south of Nova Scotia and follows a general counterclockwise circulation with a significant contribution to the Maine coastal current. The annual $S_{50}$ cycle observed at buoy L, and that appears to propagate to buoys (I, E, B) stationed in the

<table>
<thead>
<tr>
<th>Buoy ID</th>
<th>$r_{max}/T_{max}$</th>
<th>$r_{max}/T_{max}$</th>
<th>$V_{adv}/\text{DN} S$</th>
<th>$D$</th>
<th>$N$</th>
<th>$S^{[%]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.55/0</td>
<td>0.62/30</td>
<td>0.67/1.5</td>
<td>196</td>
<td>412</td>
<td>0.16/0.18</td>
</tr>
<tr>
<td>L</td>
<td>0.81/30</td>
<td>0.84/30</td>
<td>0.69/0.9</td>
<td>207</td>
<td>217</td>
<td>0.24/0.30</td>
</tr>
<tr>
<td>M</td>
<td>0.65/60</td>
<td>0.68/40</td>
<td>5.0/3.8</td>
<td>313</td>
<td>452</td>
<td>0.16/0.18</td>
</tr>
<tr>
<td>I</td>
<td>0.72/80</td>
<td>0.80/100</td>
<td>4.9/3.9</td>
<td>339</td>
<td>510</td>
<td>0.17/0.19</td>
</tr>
<tr>
<td>E</td>
<td>0.69/100</td>
<td>0.81/130</td>
<td>5.0/3.8</td>
<td>433</td>
<td>512</td>
<td>0.17/0.20</td>
</tr>
<tr>
<td>B</td>
<td>0.71/120</td>
<td>0.84/140</td>
<td>5.0/4.3</td>
<td>521</td>
<td>504</td>
<td>0.17/0.20</td>
</tr>
</tbody>
</table>

*Low-passed filters were applied to the time series used for correlation analysis (the positive time lag indicates current leads). $r_{max}$ = maximum correlation coefficient, $T_{max}$ = time lag (days), $D$ = distance between the location of track 100 and buoy location (km), $V_{adv}$ = advection speed (10 $^2$ m/s), estimated by the ratio of $D$ to $T_{max}$, $N$ = number of observations, $S$ = the estimate 95% significance level of correlation.

*Based on 70 day running mean low passed time series.

*Based on 450 day running mean low low-passed filter applied to anomaly (monthly mean removed) time series. All correlation coefficients reported here are significant at $p<0.001$.
MCC pathway, is reasonably consistent with the annual cycle in SSW freshwater transport Qs into the Gulf estimated by Smith et al. [2001] (see Figure 3 in that paper) at the nearby Cape Sable station on Browns Bank where a minima in Qs is observed to occur between days 180 and 220; consistent with the saltiest S50 buoy L level. An added point is that the annual surface S1 salinity minima at buoys B and E often occur near the time of the S50 minimum, but the former is largely due to local river plume impacts while the latter signal is likely dominated by advected SSW. This finding suggests that analyses using upper ocean salinity averaged from the surface down to 50 m or 100 m will conflate local and remote impacts. Overall, the results suggest that these buoy S50 measurements provide a reasonable proxy for advected SSW water mass impact on the core MCC, and by extension for Maine Intermediate Water [Hopkins and Garfield, 1979] as well.

While the seasonal cycle of S50 is clear, what is also apparent is the strong interannual variability in both subsurface salinity and current on the adjoining SS as seen in Figures (6 and 10), and 12. Several recent studies have discussed temporal variability of GoM salinity. Now with these data we see similar scales of variation for events such as the freshening in 2004–2005. This was discussed by Deese-Riordan [2009] who concluded that the freshening in 2004–2005 was not due to a fresh salinity anomaly on the adjoining Scotian shelf (e.g., at a Halifax station 2), but was otherwise unclear on attribution for this event.

A key second study finding is the apparent strong correlation observed between the SS current modulation and interior S50 variation, with higher explained variance along the core MCC (50–71%) than in deep basins.

Figure 12. Comparison of the time-varying residuals of buoy-measured salinity S50 with altimeter Vg100 across track 100 on the Scotian shelf after offsetting S50 by the time lags indicated, shown for buoys L, M, I, and B (from top to bottom). Residuals of buoy S50 and altimeter Vg100 anomaly were formed by removing a monthly climatology and then applying a 450 day running mean low-passed filter to remove annual and high-frequency variations.
(30-46%). This is a new result. The statistically significant high correlations are found at both the seasonal and the interannual scales, a result that is not clearly observed in the basins at depths below 100 m [Townsend et al., 2015]. Moreover the observed freshening and salting Gulf of Maine $S_{50}$ events and their covariance with altimeter-observed upper ocean current anomalies on the Scotian shelf also align with possible SS impacts on the deeper Jordan basin (see Figure 1) as deduced by Townsend et al. [2015]. Thus we conclude that the long-term observations used in this study show the ability to connect Scotian shelf freshwater inflow variation to fresh water transport anomalies into the GoM and MCC. At the order of 50–70% explained variance of $S_{50}$ along the MCC, these observations do show the strong likelihood of one means to examine and monitor remote forcing impact on internal GoM hydrography.

As a further test of the validity of results from the lagged cross-correlation analysis, one can estimate the advection velocities between track 100 and individual buoy locations assuming a direct path and steady state flow. In previous studies, equatorward along-shelf advection speeds have been estimated to be $\sim 7$ cm/s on the Scotian Shelf from Cabot Strait to Halifax using either observations [Drinkwater et al., 1979; Smith and Schwing, 1991] or modeling studies [Urrego-Blanco and Sheng, 2014]. On the shelf of Georges Bank and on to the Mid-Atlantic Bight, advection speeds of 3–7 cm/s were estimated using the propagation time of shelf water volume defined as less than 34 psu salinity [Mountain, 1991, 2003], and are consistent with measured shelf mean downstream flow [Beardsley et al., 1976]. A recent modeling work by Li et al. [2015] shows that the estimated time scale of advection from Scotian Shelf to the Jordan Basin is around 60 days, consistent with our time lag estimate. The estimated advection speeds from SS to the GoM buoy sites in terms of the present study data are given in Table 4. A velocity estimates range from 3.8 to 9.0 cm/s from the SS track 100 to the GoM coastal shelf, somewhat higher for the eastern shelf sites than in the western shelf. On average, it is $5.9 \pm 1.8$ cm/s, consistent with previous studies [Mountain and Manning 1994; Deese-Riordan, 2009; Urrego-Blanco and Sheng, 2014; Li et al., 2015].

Somewhat outside the scope of this study is the question of a recent regime change in the regional hydrography. Townsend et al. [2015] and Smith et al. [2012] postulated an increase in equatorward advection on the Scotian shelf for 2004–2008 and freshwater flux into GoM versus that in the mid-1990s. The altimeter records provide SS current measurements $V_{9100}$ back to 1992. Inspection of the $V_{9100}$ residual time series in Figure 10 do not directly indicate a regime change within the period of 1993–2016, nor are consistent with shifts in the NEC or Jordan Basin noted in Smith et al. [2012]. Rather the data do appear to show frequent multiyear reversal periods (weakening, then strengthening of downstream flow) with relaxation seen 1993 to mid-1996, mid-2001 to mid-2004, mid-2005 to 2007, each followed by 16–24 month periods of substantial acceleration of downstream flow. But if a decadal regime shift can be identified, it might lie between 1993–2003 and 2004-present. If one uses this somewhat subjective dividing line for data in Figure 10a, there is a mean positive velocity (relaxation) anomaly of $+0.5$ cm/s for the first period and a negative (increase) velocity anomaly of $-0.4$ cm/s for the latter period. This represents roughly a 15% change assuming a mean 6 cm/s down-coast current. Extending both the GoM salinity and SS current records forward in time should add more clarity, as may a more detailed analysis and/or model data assimilation of the altimeter and coastal tide gauge data [e.g., Smith et al., 2012].

4.2. Controls on SS Current Variability: Role of Local Wind Forcing

Smith [1989] investigated seasonal and inter-annual variability in hydrographic properties for the northern channel entrance to the GoM based on two long-term moorings (1978–1985) near Cape Sable on the southwest SS. The authors reported significant correlations between the along-shelf wind stress and the alongshore current (as well as the mid-deep depth salinity anomalies) and marginal correlation between cross-shore wind stress and alongshore current near Cape Sable. The latter is consistent with wind-induced Ekman balance dynamics. On the broader Scotian shelf, the predominantly downstream along-shelf flow transports the colder and fresher waters influenced by both the Labrador Current and inputs from the Gulf of St. Lawrence, with some fraction entering the Gulf from the southwest SS. How does the local wind forcing influence the overall alongshore flow, in particular, on the SS near the key study altimeter track 100? A recent study by Li et al. [2014] investigated the impact of regional along-shelf wind stress on the alongshore flow and salinity in the region, and reported that local wind forcing plays a role in adjusting the along-shelf flow at interannual time scales. A so-called “valve” mechanism was proposed where along-shore wind stress increase (in the mean SW wind) serves to decelerate down-coast flow, implying less freshwater transport to the GoM. While the correlation analysis showed favorable results in 2004–2006, the proposed mechanism
failed to explain variability in several other strong freshening periods (e.g., 1997–1998). The authors suggested several additional mechanisms that may be involved, including the cross-shore wind contribution to the alongshore current (Ekman effect). In this region, the strongest modulation of this component is tied to the fall-to-winter increase in winds from the north.

To examine this issue in more detail, a sensitivity analysis of the SS coastal current response to wind stress direction is performed at both the seasonal and interannual time scales. First, the wind record is decomposed into along-shore ($\frac{250}{2}$) and cross-shore ($\frac{160}{2}$) wind stress components based on the southwest SS orientation as for early studies [Li et al., 2014; Brown, 1998]. Figure 13 shows the 70 day low passed time series of these winds as measured at Yarmouth (see Figure 1), along with the altimeter-based along-shelf current anomaly $V_{g100}$. Somewhat unexpectedly, $V_{g100}$ variation is not well correlated with the along-shelf wind stress (Figure 13, top), but it is significantly correlated with the cross-shore stress ($R = 0.60$; Figure 13, bottom). Results indicate that increased SW flow on the Scotian Shelf are related to increased offshore (NNE) winds.

Figure 14 shows correlations between the altimeter-derived along-shelf current anomaly $V_g$ (derived on track 100 at the shelf edge, on the shelf, and both, and for track 024 at the shelf edge) and varying wind stress direction $\theta$ (x-axis), given as the relative direction away from the along-shore wind stress direction (+250°). In general, the sensitivity analysis shows that a significant along-shelf current variability response ($R > 0.5$) to local wind forcing holds for a relatively wide range wind directions when both seasonal and inter-annual signals included time series.

At the seasonal scale (Figure 14: left panel) and for the shelf edge currents $V_{g100}$ and $V_{g24}$, the most sensitive forcing orientation is $\theta = 30°$ (+220°), relatively close to the alongshore wind. The positive sign in the correlation reflects the fact that increased wind stress from this direction is upwelling favorable,
decelerating the mean downstream flow. Note however, that at $h_{508}$ ($125^\circ$), considered the alongshore direction, the correlation falls to values as low as 0.2 for shelf edge segments.

For current variation measured on the shelf rather than at the shelf edge, $V_{g100}$ is most sensitive to wind forcing from a relative direction of $\theta \sim 70^\circ$ ($180^\circ$), and the elevated correlation holds for a wider range of forcing directions. This implies that a change in the cross-shore stress appears to impact the along-shelf flow more significantly than for along-shore wind change when closer to shore on track 100. In other words, from this analysis, increased offshore wind stress enhances negative along-shelf current anomalies, i.e., favoring an increased mean downstream flow, with a correlation coefficient of 0.61.

A similar sensitivity analysis of stress direction impact on along-shelf current was carried out for the interannual time scale variability with the results given in Figure 14 (right panel). This analysis was performed after applying a 450 day running mean to the time series. At this longer time scale, the most effective local wind stress fluctuation orientation is $\theta = 30^\circ-40^\circ$, ($210^\circ-220^\circ$), yielding a correlation of $\sim 0.6$, and aligning closer to the local along-shelf direction. The result agrees well with what was reported in Li et al. [2014]. Moreover, the results also indicate that the maximum response of along-shelf flow interannual variability to the local wind forcing holds for a significantly narrower range of wind forcing directions when compared with data that includes the seasonal variability.

This statistical wind-forcing sensitivity analysis suggests that both local along- and cross-shelf wind stresses play some role in modulating the local hydrodynamic conditions. This could be attributed to the particular bathymetry on the southwest SS where local bathymetry at Cape Sable is orthogonal to the broader shelf break that guides the main along-shelf flow. An alternative explanation could lie in the overall topography of the Scotian Shelf and Gulf of St. Lawrence region where a cross-shore wind near...
Halifax is an alongshore wind just north of Nova Scotia, a site where the Gulf of St. Lawrence feeds into the SS coastal current and where wind stress modulation has been predicted to remotely impact currents on the SS and into the GoM [Urengo-Blanco and Sheng, 2014]. However, the full impact of local and remote winds on this along-shelf current at seasonal and interannual scales is uncertain. It is left for future studies to investigate the potential net influence of local nonlinear or remote Ekman-driven flows on both the geostrophic and total currents.

5. Conclusion

In this study, more than a decade of subsurface salinity $S_{50}$ observations from GoM NERACOOS buoys provides an opportunity to precisely identify the timing and magnitude of $S_{50}$ variability throughout the Gulf at a broad range of time scales. More than two decades of satellite altimeter data provide new insight on the along-shelf current variations within the Nova Scotian and Gulf of Maine shelf system. The study has investigated both seasonal and interannual variability of observed subsurface salinity in the interior basins and coastal shelf of the Gulf of Maine and satellite altimeter-derived upper ocean geostrophic current $V_g$ on the NWA shelf, and clearly identified correlations between the two.

Long-term altimeter observations appear to provide new information and a potential proxy for temporal variability in Scotian Shelf freshwater inflow to the Gulf of Maine. MCC buoy-observed $S_{50}$ time series show significant freshening of internal GoM waters occurred in mid-2004 to 2005 and 2010–2011 following acceleration in down-coast SS currents, while relaxation of SS currents led to saltier water conditions in 2002 to mid-2004 and 2012–2015. Time lagged cross-correlation analysis indicates that $V_{g100}$ modulation explains a significant amount of subsurface salinity $S_{50}$ variability, particularly along the coastal shelf where the MCC passes, at both seasonal and interannual time scales, and with relatively higher correlation levels observed along the MCC than for that observed using the deep basin buoys. For the MCC buoys, the maximum observed correlations are 0.69–0.81 (explaining about 48–66% variance) and greater than 0.8 (explaining about 64–71% variance) for the seasonal and inter-annual time scales, respectively. For basin buoys, the explained variance is at the range of 30–46%. The time lags between SS current $V_{g100}$ and $S_{50}$ along the GoM coastal shelf provided estimates of advection speeds of 5.9 ± 1.8 cm/s on average, highly consistent with those previously reported. Clearly shown, subsurface salinity $S_{50}$ in the interior GoM, especially along the MCC, is significantly correlated with variation in the equatorward along-shelf advection along the general Gulf MCC pass-way. Differing results obtained using the coastal MCC buoys (L, I, E, B), and basin buoys (M and N) are consistent with control by the GoM inflow from the Scotian Shelf via the northern channel pathway near Cape Sable.

An investigation into how along-shelf current on SS are influenced by local wind forcing fluctuations at seasonal and interannual time scales shows that both local along-shelf and cross-shelf wind stresses modulate local hydrodynamic conditions such that diagnosis neglecting the cross-shore winds will neglect significant forcing factor in the southwest Scotian Shelf. Further investigation of factors impacting the Gulf of Maine inflow pathways will certainly also benefit from a broader scale analysis of remote forcing on the Shelf flows that include the Gulf of St. Lawrence and Cabot Strait.

Finally, a key study implication is that the long-term altimeter observations in the region can provide valuable dynamic inputs for data assimilation into regional circulation models. This appears particularly true for the southwest SS and is the topic of a modeling study now in progress.

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