Winter surface salinity in the northeastern Gulf of Maine from five years of SMAP satellite data

Grodsky Semyon A. ^{1,*}, Vandemark Douglas ², Reul Nicolas ³, Feng Hui ², Levin Julia ⁴

¹ Department of Atmospheric and Oceanic Science, University of Maryland, College Park, USA

² University of New Hampshire, Durham, USA

³ IFREMER, University Brest, CNRS, IRD, Laboratoire d'Océanographie Physique et Spatiale (LOPS), IUEM, Brest, France

⁴ Rutgers University, New Brunswick, NJ, USA

* Corresponding author : Semyon A. Grodsky, email address : senya@atmos.umd.edu

Abstract :

Wintertime freshwater transport into the Gulf of Maine (GoM) is typically controlled by a seasonal velocity increase in the fresh upstream Nova Scotia Current (NSC). Repeat satellite observations from the Soil Moisture Active Passive mission have mapped significant GoM surface salinity anomalies in four of five recent winters. These satellite data are used in combination with Jordan basin buoy and model datasets to investigate the likelihood that variable wind-forcing of the NSC contributed to these anomalies. This stems from regional ocean circulation studies suggesting that strengthening of alongshore southwesterly winds on the Scotian shelf weakens NSC transport into the GoM, while cross-shore southeasterly winds may also contribute to NSC weakening, and vice versa. A 17-year time series analysis of GoM buoy and satellite data shows that near-surface salinity in the eastern GoM can indeed be modulated by both alongshore and cross-shore winds through their impact on the NSC. The NSC geostrophic current modulation correlates with buoy-observed surface salinity anomalies when using a one month advective lead time. For a shorter 5-year period, a SMAP-derived salinity anomaly index in the eastern GoM indicates a similar relation to NSC variation and also correlates with Scotian Shelf wind anomalies. The relationships between winter wind and NSC transport variability are confirmed using output from a 19-year high resolution global ocean simulation. Attribution of these local wind anomalies to basin-scale atmospheric patterns shows that most years with strong winter GoM freshening coincide with weakening of a North Atlantic Oscillation-like wind pattern. But its reversals do not always correspond with a saline GoM. This contrast suggests that wind forcing more directly controls fresh winter GoM anomalies but not salty. Instead, they are partly due to density-driven advection from neighboring warm and saline Atlantic slope water including episodic Gulf Stream instabilities.

Highlights

► SMAP detects significant eastern GoM SSSA (up to 1 psu) in four of five winters. ► Jordan basin SSSA correlation with Nova Scotia Current geostrophic anomaly is ~0.7. ► Only half of the above correlation is explained by wind-driven current variations. ► Eastern GoM satellite SSSA index is better indicator of fresh Scotian Shelf inflows.

1. Introduction

Gulf of Maine (GoM) salinity changes at interannual to decadal time scales are accompanied by biochemical shifts that can, along with changing temperature, ultimately impact water column stratification as well as the ecosystem across many trophic levels (McGillicuddy et al., 2011; Mountain and Kane, 2010; Townsend, 1991; Runge et al., 2014; Lorz et al., 2019; Li et al., 2014). Detection and prediction of both thermohaline variability and trends are topics of intense recent focus (Pershing et al., 2015; Hare et al., 2016). The study of the ocean circulation within the connected coastal Scotian Shelf, Bay of Fundy, and GoM systems has a rich history using both hydrographic data and models to address dynamics that are largely defined by the complex bathymetry and coastline (for reviews, see Townsend et al., 2015; Loder et al., 1997). Yet there is still a lack of certainty regarding the mechanisms that control competing inflows to this marginal sea from offshore and from the adjoining upstream Nova Scotian Shelf. Investigation of these controls has considered forcing that spans from local air-sea fluxes and tides to remote forcing via Arctic ice dynamics and atmospheric teleconnections (Greene et al., 2013; Mountain, 2012; Greene and Pershing, 2000). While the annual cycle of near-surface salinity in the Gulf of Maine and adjoining shelves is well documented (cf. Mountain and Manning, 1994; Richaud et al., 2016; Bisagni, 2016), further data on interannual change are needed to clarify the strength of key advective-forcing mechanisms and how they may be used to monitor and model thermohaline variability. Several recent studies have used a combination of satellite altimetry and regional and satellite wind data (Li et al., 2014; Feng et al., 2016; Grodsky et al., 2017) to confirm the importance of regional wind forcing on the amount of Scotian Shelf water transport to the Gulf (Smith, 1983). One salient component of Gulf circulation is that cold freshwater inflow from the Scotian Shelf is greatest each winter, often freshening surface layers in the eastern Gulf of Maine. The new time series of region-wide surface salinity data provided by the SMAP (Soil Moisture Active Passive) satellite since 2015 leads one to ask - Can we use a

complement of weekly-to-monthly satellite observations over the eastern Gulf of Maine winter to improve understanding about the drivers of interannual salinity change in the Gulf of Maine? This study assesses this question with observations spanning five recent winters.

The two major source waters for the GoM enter first into the eastern Gulf. These inputs are NW Atlantic slope sea waters and Scotian Shelf Water (SSW), with respective inflow via the Northeast channel (NEC) and along the shelf SW of Cape Sable, Nova Scotia (see Figure 1). NEC inflow primarily consists of Warm Slope water (WSW), and less frequently Labrador Slope Water (LSW), Gulf Stream meanders, or warm-core ring water (WCR). SSW enters as Cape Sable Inflow (Smith et al., 2001; Smith, 1983) and can contrast significantly with NEC inflow, being significantly colder and fresher and with comparable transport variability. Until recently, the prevailing conceptual model for advective influence on Gulf of Maine water masses, nutrients, and biochemistry was focused on the NEC and variability, variation in its larger subsurface inflows due to wind (Ramp et al., 1985), and on observed differences between WSW and infrequent episodic LSW or warm-core ring inflows (e.g. Mountain, 2012; Brooks, 1987; Grodsky et al., 2018b). But recent analyses of long-term continuous moored observations within the Gulf of Maine suggest that more focus should be placed on observing and understanding the complex balance between NEC and Cape Sable Inflow (CSI) on interior Gulf of Maine water masses, both at the surface and for deeper layers (Smith et al., 2012; Townsend et al., 2015). In particular, observations in the last decades at Jordan Basic Buoy M01 indicate an increased amount of fresh SSW in the Gulf, presumably carried by the CSI from the Scotian Shelf, rather than through the NEC. These studies also emphasize the need to improve long-term monitoring of both NEC and CSI inflows and the factors that control them, particularly just upstream on the adjoining Scotian Shelf (see Figure 1) where both wind and remote freshwater advection are considered as factors modulating the Nova Scotia Current (NSC) and its delivery of SSW to the Gulf. A recognized limit of these buoy-focused investigations is the reliance on just two locations (station M and N, Townsend et al., 2015) within this fairly complex circulation, and with no ongoing measurements near the critical Cape Sable shelf.

In this new attempt to examine controls on upper ocean salinity in the Gulf of Maine we choose to focus on the eastern GoM, defined here to span roughly from Brown's Bank in the south to Jordan Basin to the north (see Figure 1). Mountain and Manning (1994) observed that the surface salinity in this region is distinct from the interior Gulf largely because it first receives

water from the NEC and CSI, whereas advection and mixing from tides, winds, and local rivers lead to its decorrelation with surface salinity in the interior Gulf. This study will also focus on the winter period and spatially-mapped sea surface salinity anomalies (SSSA) observed in successive winters. Given this seasonal focus, the main control we seek to further assess is wind forcing and its resulting impact on local circulation and eastern Gulf of Maine surface salinity. The NSC and its characteristics on the SW Scotian shelf will thus be central to the investigation (see Smith, 1983; Smith et al., 2001; Smith et al., 2012; Han et al., 1997; Brickman et al., 2016). And while alongshore SSW impacts on the Gulf of Maine SSSA are a focus, it is also understood that there are many observed examples of episodic cross shore exchange (e.g. Grodsky et al., 2018b) within the NEC, upstream on the Scotian Shelf (Brickman et al., 2018), and region-wide thermohaline changes (Holliday et al., 2020; Gawarkiewicz et al., 2018) that may require consideration within the analyses.

This study will also attempt to extend findings made using these five SMAP-observed winters using longer multi-decade model and buoy datasets. One objective in the extended analysis is to revisit the topic of N. Atlantic basin-scale atmospheric control of seasonal winds and linkages to indices such as the North Atlantic Oscillation (Hurrell et al., 2003). Multi-year NAO variations produce a tri-pole gyre-scale sea level pattern with amplified subpolar gyre and stronger, coastward-shifted Gulfstream during prolonged NAO+ events (Hakkinen and Rhines, 2004; Volkov et al., 2019; Chafik et al., 2019). The work of Li et al. (2014) suggested that, at least at the 450-day time scale, NAO impacts on the Scotian Shelf along-shore wind forcing has been weak or negligible in recent decades, while Grodsky et al. (2017) reported that shelf surface salinity is positively correlated with NAO variations. How do winter-period forcing data and surface salinity observations in the eastern Gulf of Maine relate to NAO forcing?

Several recent studies using satellite SSSA data in this region have illustrated that monthly surface salinity variations from the seasonal mean are often large enough (~ 1 psu) to overcome known L-band satellite radiometer detection limits in cold water ($SST < 6 - 8^\circ C$) conditions (Grodsky et al., 2018a; Grodsky et al., 2018b; Reul et al., 2020). The quality of coastal SMAP SSS data is also being improved to provide more accurate measurements within 50 – 100 km of the coast (Meissner et al., 2019). Thus there is a promise that now more than 10-year long satellite SSS data (Reul et al., 2020) may enhance the existing observing system. The following study uses a complement of satellite sea level, SST, SSS, and wind data to evaluate the possible

interannual impact of regional wind variations on GoM freshwater anomalies from 2015-2020. This 5-year SMAP time series is then used in combination with longer in-situ observations and numerical simulations to evaluate the relative importance of wind-driven horizontal advection in controlling surface salinity within the Gulf of Maine and to shed further light on approaches for monitoring the two primary Gulf inflows.

2. Data and Methods

Satellite salinity: This study relies on satellite SSS from the SMAP mission. Global Level 3 SMAP SSS is available daily as an 8-day running mean on a 0.25° grid (version 4.0 produced by the Remote Sensing Systems, www.remss.com/missions/smap, Meissner et al., 2019). The surface footprint of each measurement is 39×47 km so the effective resolution is close to 40 km. To decrease satellite SSS measurement noise, we use monthly averaged 70 km-smoothed data. Although satellite SSS agrees with in-situ measurements in the warmer tropics to within ~ 0.2 psu (Lee, 2016; Reul et al., 2020), its accuracy at higher latitudes and approaching coastlines is less certain due to several limitations that lead to seasonally dependent SSS biases (Meissner et al., 2016). For the northwestern Atlantic, (Grotsky et al., 2018a) found a significant positive bias in absolute SMAP SSS coastward of a 0.5% antenna land contamination flagging, which occupies a significant portion of the GoM (Grotsky et al., 2018b). As shown by e.g., (Boutin et al., 2016), the SSS anomaly, which is defined as the difference computed relative to a monthly satellite SSS climatology, effectively removes such seasonal biases along with the real seasonal cycle. For this study, the monthly seasonal cycle at each grid point was estimated as the time mean for each calendar month (based on the entire available SMAP period, April 2015 - onward).

Other satellite data: This study relies on satellite SST from the Canadian Meteorological Centre. It is Level 4, 0.1° combined infrared, microwave, and in-situ daily analysis (<https://podaac.jpl.nasa.gov/dataset/CMC0.1deg-CMC-L4-GLOB-v3.0>) that is used for SMAP processing. The inclusion of microwave SST is important in this cloudy region, especially during the winter months. Monthly absolute dynamics topography and surface geostrophic currents are obtained from the AVISO multi-satellite merged altimeter dataset. These data are now distributed through the Copernicus Marine Environment Monitoring Service (<http://marine.copernicus.eu>). Even in coastal areas, these altimeter data show reasonable temporal variability verified against tide gauges (Cipollini et al., 2017). Gridded 10 m neutral

winds merging measurements from all major satellite scatterometer missions (1993-2018) are described in (Bentamy et al., 2017) and available from the Ocean Heat Flux Project at <https://wwz.ifremer.fr/oceanheatflux/Project>. These data are extended up to the present using ASCAT scatterometer winds described in (Bentamy and Fillon, 2012).

Mooring data: The University of Maine Ocean Observing System (UMOOS) Gulf of Maine Moored Buoy Program operates several GoM coastal and deeper basin moorings (<http://gyre.umeoce.maine.edu/buoyhome.php>) and is a part of US northeast coastal monitoring of the NERACOOS Program. We focus on the mid-basin mooring (M01, 2003-present, Figure 1) located in Jordan Basin in the northeastern GoM. This buoy monitors temperature and salinity, including near-surface measurements at $z = 1\text{m}$. Daily buoy salinity anomalies were computed by subtracting the monthly seasonal cycle (based on the full buoy data temporal coverage) resampled daily using cubic spline interpolation. All buoy data have been averaged daily, in part to reduce significant variability associated with tides.

Model simulations and atmospheric reanalysis: Model data are used as supplementary data to confirm observation-based findings. To examine coastal wind-induced ocean responses along Nova Scotia and adjacent coasts, this study uses a multi-decade integration of an $\sim 0.1^\circ$ (tri-polar grid) eddy-resolving POP2 ocean circulation model driven by interannually varying atmospheric forcing from the Coordinated Ocean Ice Reference Experiments and climatological river discharge. A more detailed description of these model simulations was presented in e.g., (Johnson et al., 2016). Some aspects of this model validation for the NW Atlantic shelf are present in (Grotsky et al., 2017). In particular, it reproduces well the magnitude of salinity variability along the shelf slope front and reasonably simulates shelf currents and their variability (see Fig. 9 and Fig. 11 therein), including the Nova Scotia and shelf-edge Currents. Mean sea level atmospheric pressure data are taken from the ERA5 atmospheric reanalysis (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>).

Throughout this paper, anomalies are defined as deviations from the seasonal cycle.

3. Results

a. Seasonal cycle of surface fields

Mixed layer salinity in the GoM has intermediate values between the freshest SSW and more salty WSW. The southwestward flow along the seaward side of Nova Scotia (the NSC) represents the freshest water in the region (Figure 2) and the main supply of fresh and cold water into the GoM. The impact of this freshwater advection on internal GoM salinity depends on several factors, including salinity contrast and inflow magnitude. In winter, while SSS in the central and western parts of the GoM increases due to mixing and entrainment, SSS in the eastern GoM and to the coast of Nova Scotia decreases due to low saline near-surface Sable Island inflow that peaks in January - February (Smith, 1983). The large wintertime zonal salinity gradient suggests that the fresher upstream SSW inflow may have a larger impact on internal GoM salinity in winter. In contrast to the winter circulation pattern (Figure 2a), NSC surface geostrophic current is greatly reduced in the summer with little or no evidence of low SSS intrusion into the GoM (Figure 2b).

The seasonal variations of local winds are in line with the seasonal variations of the NSC. Summer deceleration of the NSC is, in part, related to seasonally prevailing southwesterly winds, which counteract the NSC by setting up the seasonal seaward cross-shore pressure gradient through upwelling adjustment processes (Li et al., 2014). But local winter winds are mostly offshore (Figure 2a). This winter, the northwesterly wind anomaly amplifies the local southwestward Ekman response and leads to winter NSC acceleration (see also discussions later on). Overall, the seasonal analysis in Figure 2 suggests that freshwater intrusions into the GoM are seasonally dependent. They amplify in winter along with seasonal NSC acceleration, which is generally consistent with previous studies (Smith et al., 2001; Dever et al., 2016). Additionally, the NSC may also carry salinity anomalies sourced by the Cabot Strait outflow from the Gulf of St. Lawrence and its upstream sources that pass through the Halifax section during September–October and arrive at southwest Nova Scotia later in the year (Brickman et al., 2016).

b. Spatial statistics of SSS and SST anomalies

Figure 3 shows satellite-derived SSS and SST anomalies (SSSA and SSTA) within the GoM and surrounding waters for the winter and summer seasons. Despite uncertainty due to the relatively short SMAP data record, Figure 3 indicates that winter salinity anomalies are larger than summer in the eastern GoM ($\sim 43.5^\circ\text{N}, 67^\circ\text{W}$), a result consistent with Mountain and Manning (1994).

This is likely attributed to this same fall-to-winter maximum in NSC inflow off Cape Sable. Joint statistics of regional surface T and S anomalies may shed further light on their origins. As shown by e.g., Flagg et al. (2006), the correlation between upper ocean salinity and temperature anomalies is nominally positive when produced by horizontal advection, but negative when produced by vertical exchange due to the presence of the subsurface salinity maximum e.g., (Grotsky et al., 2017). Figures 3c and 3d show that during both winter and summer seasons the temporal correlation of salinity and temperature anomalies is positive over the Slope Sea. This positively correlated area extends from the Gulf Stream core (identified as maximum sea level variability area) to the shelf-slope front (identified in Figure 3 as the maximum SSS variability area). One explanation for this correlation is advection from warm and salty Gulfstream warm core meanders and rings e.g., (Csanady, 1979) that lie between the Gulfstream and the shelf-slope front. These meanders normally don't penetrate onto the shelf where local depths are shallower than their vertical scale. This leads to a weak or negative anomaly correlation coastward of the shelf edge (Figures 3c, 3d). Most notably for this study, a moderately positively correlated area (≥ 0.4) of anomalous SSS and SST emerges in the winter in the NE GoM, consistent with expected horizontal advective impacts due to varying NSC inflow. Results also imply that only in the winter and in the eastern half of the Gulf do SSSA variations become comparable with the much larger variability observed along the adjoining NW Atlantic shelf-break front; a front roughly following the shelf break 1000m isobath (see Figures 3a and 3b).

c. Sea surface salinity anomalies over five Gulf of Maine winters observed with SMAP

In an attempt to understand dynamical factors affecting near-surface salinity anomalies in the northeastern GoM, a seasonally-averaged SSS anomaly map is provided in Figure 4 for each winter during 2015-20 along with additional and potentially relevant near-surface observations. According to satellite SMAP records, SSS conditions in the GoM were close to neutral (weak anomalous SSS) in the winter of 2015-16 (Figure 4a). This was followed by a sequence of fresh and salty events in the following years (Figures 4d, 4g, 4j, 4m). Interestingly, not all GoM salinity variations have a corresponding imprint in the SST anomaly fields. While the 2017-18 and 2018-19 events (Figures 4g, 4j) have positively correlated SST signatures (Figures 4h, 4k), earlier years do not (compare Figures 4a, 4d and Figures 4b, 4e). The latest freshening observed in the winter of 2019-20 (Figures 4m, 4n) presents yet another example of GoM freshwater intrusion not accompanied by colder SST. This lack of correspondence is not unexpected given

strong ocean heat loss in winters within the GoM. While upper ocean salinity is more conservative and most strongly affected by advection processes (Foltz et al., 2004), mixed layer temperature is also affected by the net surface heat flux (Foltz et al., 2003) and this may alter and mask advection-induced temperature anomalies.

Dynamical conditions in Figure 4 (right column) are shown one month before corresponding salinity patterns in Figure 4 (left column) consistent with the upstream advective timescales observed here in winter e.g., (Han et al., 1997; Feng et al., 2016). Although the accuracy of gridded altimetry sea level and its related geostrophic currents deteriorates approaching coasts e.g., (Feng et al., 2018), the altimeter sea level will be analyzed for the presence of coastal patterns affecting the NSC. This altimeter application is based on the (Feng et al., 2016) analysis that shows that the variations of altimeter-derived geostrophic current on Nova Scotia are reasonably linked with the variations of GoM salinity. Geostrophic balance in the southwestward NSC suggests the presence of a sea level high along the Nova Scotian coast. Year-to-year variations of this coastal sea level high agree with anomalous SSS in the northeastern GoM. During GoM freshening years (Figures 4d, 4j, 4n), the apparent coastal sea level high was present (Figures 4f, 4l, 4o). By contrast, the salty event of 2017-18 (Figure 4g) shows a virtual absence of this Nova Scotia coastal sea level high (Figure 4i) and the greatly attenuated NSC. In turn, this suggests that abnormally weak NSC freshwater transport in the winter of 2017-18 contributed to the salty anomaly in Figure 4g. Anomalous wind patterns in Figure 4 (right) are highly variable and we will return to their analysis after examining longer term joint variability of regional winds and sea level.

d. Salinity anomaly analyses at mooring M01, 2003-2020

The seasonal estimates of SSSA variability shown in Figure 3 are derived from relatively short SMAP satellite time series (since April 2015) that include only five winters. To sample over more winter observations, we turn to a potential proxy for eastern GoM SSSA by using data from mooring M01 in Jordan Basin (see Figure 1).

i. Vertical structure of buoy salinity anomaly at the M01

The monthly M01 buoy data from 2003-2020 provide vertically-resolved anomalous salinity (Figure 5a) with limited dropouts across the 17-year record. It is fairly well correlated throughout the water column at monthly time scales suggesting that SSS is a good indicator of salinity

variability at deeper levels. Vertical EOF decomposition of anomalous salinity indicates that nearly 66% of the variance is accounted for by the first mode, thus salinity variations are mostly in phase through the full water column. The second mode indicates that 20% of the variance corresponds to out-of-phase oscillations between the upper 50 m and depths below 50 m (Figure 5c). This partitioning is inferred from monthly salinity anomalies and may not hold at shorter periods. In line with satellite SSS in Figure 3, in-situ salinity data also suggest that anomalous salinity magnitude peaks in winter months (Figure 5d) and decreases by at least a factor of two in summer months. This is also true for the anomalous salinity averaged over the upper 50 m and the leading EOF amplitude (PC1). The seasonal magnitude of the second EOF also peaks in winter but has a secondary extremum in summer probably reflecting the seasonal mixed layer shallowing, which virtually separates mixed layer variability from that at sub-thermocline depths.

ii. Buoy-SMAP comparison

During the SMAP period (2015-onward), daily averaged near-surface buoy M01 salinity anomaly measurements inside the GoM show good agreement with collocated SMAP SSSA (Figure 6a). The temporal correlation is ~ 0.6 and the standard deviation (STD) is 0.38 psu. During this period, available buoy salinity records capture the three upper ocean winter anomalies of 2018, 2019, and 2020 (Figure 6b). These buoy data mostly agree with SMAP data for a salty event in winter 2017–18 and fresh features in early 2019 and 2020 (Figure 4). The 2017-18 salty event was quite unusual. Buoy M01 T/S analysis characterized it as a ~ 100 m deep near-surface inflow composed of modified Atlantic WSW, typically observed only at depths below 100 m and previously unobserved at the surface in this 15-year buoy record (Grodsky et al., 2018b). It originated from interactions between a preexisting open ocean salty anomaly and a warm Gulf Stream meander that advected high salinity water onto the shelf and then into the northeastern GoM via the NEC—arriving at the station M01 as an about 1psu surface-trapped salty feature in late fall 2017 and lasting through early 2018. In the next two years (2019 and 2020), fresh winter anomalies (~ -1 psu) are present in M01 observations (Figure 6). But in the first two years, buoy and satellite salinity data are closer to mean winter values. This suggests that the Jordan Basin buoy location may be less than ideal for monitoring surface water intrusions from Cape Sable because this advective pathway into the GoM is

centered on the 100 m isobath off western Nova Scotia; a pathway 60-80 km east of the M01 deep basin mooring (Figure 3a).

The collocation of SMAP with M01 data in Figure 6a is done using the nearest SMAP grid point criterion. SMAP data include a random noise particularly evident in 1-grid point data. It leads to noticeable scatter in collocated SMAP time series. Another factor of SMAP-buoy deviation is in the difference between spatial sampling of satellite and mooring data. While the SMAP SSS is spatially smoothed over about 70 km, the mooring M01 performs pointwise measurements. As mentioned above, the particular M01 location maybe not ideal for capturing GoM intrusions. Some salinity events get unobserved in pointwise buoy records but get captured in a 70-km wide satellite ground swath. An example of such spatial sampling discrepancy is the December 2016 fresh event that is partly captured by the SMAP but is almost absent in the buoy data (Figure 6a, see also Figure 4d and discussions of eastern GoM satellite SSSA index in Summary). There also exists a seasonally-dependent retrieval bias in SMAP data, with positively biased SMAP SSS in the summer (compare buoy and SMAP seasonal cycles in Figure 6a). By design, SMAP SSSA estimates remove any seasonal retrieval biases (along with the real seasonal cycle) in SMAP SSSA estimates. The resulting spatial SSSA maps capture salinity anomalies associated with eastern GoM intrusions (Figure 4). In part, detection is possible because the relatively large SSSA magnitudes are comparable to or even exceed that of the seasonal SSS cycle (see Figure 6a for salinity at the buoy M01).

e. Regional winds and sea level and their links with GoM salinity

i. Multivariate EOF analysis of altimeter sea level and winds

Focusing on wind-induced variability in the GoM and surrounding areas, we perform a multivariate Empirical Orthogonal Function (EOF) analysis of anomalous monthly sea level and winds based on the entire altimeter record since 1993. The resulting time series is only shown from 2003 when M01 buoy observations become available (Figure 7). To avoid possible impacts of strong sea level anomalies associated with Gulf Stream meanders, the analysis domain excludes areas where the STD of sea level exceeds 6 cm. The leading mode of variability is associated with alongshore winds (Figure 7a). Hereafter the alongshore component is defined as a projection on the general orientation of Nova Scotia seaward coastline, 26° counterclockwise from the east, positive in northeastward direction. This is consistent with the valve mechanism of

(Li et al., 2014) suggesting that upwelling-favorable southwesterly wind anomalies produce a sea level low along Nova Scotia and thus decelerate the NSC and its GoM inflow (Figure 7a). This EOF1 pattern also includes a northeastward gradient of sea level along the Nova Scotia seaward coast that balances the northeastward wind stress anomaly. The sea level low associated with this mode develops along the entire coastal region of the analysis domain and suggests below normal cyclonic circulation in the GoM during positive EOF1 phases.

The second mode of variability (Figure 7b) is associated with cross-shore winds. Surprisingly, the strengthening of onshore winds also decreases sea level along the seaward side of Nova Scotia and thus decelerates the NSC. Note that the sea level pressure gradient associated with the coastal sea level low cannot balance the cross-shore wind stress component. Instead, the sum of the two is balanced by the Coriolis force associated with the anomalous NSC. In distinction from the leading mode (Figure 7a), the sea level low develops only along coastal Nova Scotia and doesn't extend into the northwestern GoM. This suggests that GoM salinity anomalies produced by Nova Scotia cross-shore winds may be observed in the northeastern GoM, but may not extend further north and then west to impact the Maine Coastal Current as seen with mode #1.

ii. Wind-driven NSC variability

Comparing temporal amplitudes (PC) of the two leading EOFs with anomalous salinity at the M01 mooring (Figures 7c) deliver mixed results. Note that the EOF sign is chosen in such a way that negative/positive EOF amplitude in Figure 7a corresponds to northeasterly/southwesterly wind anomaly, accelerated/decelerated NSC, and fresher/saltier expected salinity in the northeastern GoM, respectively. The above relationships imply a positive correlation between PC and surface salinity in the northeastern GoM. In fact, during buoy M01 records (Figure 7c), strong negative PC1 episodes in the winters of 2005 and 2010 resulted in apparent fresh events in the GoM. But other PC1 wind events have weaker, if any, imprint on GoM salinity.

The geostrophic velocity anomaly averaged over the NSC index area shown in Figure 2a ($NSCA = u' \cos \alpha + v' \sin \alpha$) has only a marginal correlation with each principal component of the multivariate sea level and wind EOF (PC1 and PC2; CORR ~ 0.3 , see Table 1). Here, u' and v' are the eastward and northward velocity anomaly components, respectively, and $\alpha = 26^\circ$ is the average orientation of coastal Nova Scotia (counterclockwise from the east). Because the two

EOF modes are additive, a net anomalous wind-driven term ($NSCA_w$) can be defined as $NSCA_w = -\frac{g}{f} \cdot \frac{\partial H}{\partial x} \cos \alpha + \frac{g}{f} \cdot \frac{\partial H}{\partial y} \sin \alpha$, with $H = PC1 \cdot EOF1_H + PC2 \cdot EOF2_H$ as estimated from the first two sea level components of the multivariate EOF (Figures 7a, 7b). This term has a higher correlation with the altimeter-observed NSCA (~ 0.4 , Table 1) than for either individual mode. Yet it is found that the correlation level of ~ 0.67 (Figure 8d) between buoy M01 salinity and the total geostrophic anomaly, NSCA, is almost double that for this net wind-driven component ($NSCA_w$, $CORR \approx 0.35$ in Table 1). This implies that NSC freshwater transport variability is also forced by factors unrelated to the local winds. As one example, the correlation between NSCA and $NSCA_w$ is weak across the extended 2012-2016 time period in Figures 7 and 8. As discussed in Grodsky et al. (2017), this shelf-wide salinity period was related not only to NSC deceleration but also to shelf-edge current deceleration.

iii. Patterns of flow connectivity

Because the NSC carries relatively fresh water, it is expected that its inflow anomaly has the largest effect on near-surface salinity inside the GoM. At mooring M01, salinity anomalies lag the NSC transport anomaly by a month (Figure 9a) and impact mostly the upper 75m. Given NSC velocity variability ($STD = 0.015 \text{ m s}^{-1}$), the regression magnitude in Figure 9a corresponds to ~ 0.2 psu salinity variation in response to one STD deviation of the current. Interestingly, there is also a weaker but statistically significant correlation between NSC transport anomalies and salinity at the NEC GoM mooring N01 (Figure 1 and Figure 9b). This suggests that a portion of NSC freshwater transport veers SW around Browns Bank and enters the GoM along the northern flank of the NEC (Figure 2a).

The availability of moderately long (2003 - present) salinity records at the moorings M01 and N01 permits further insight into the flow connectivity along the Nova Scotia – GoM region. Figure 9c depicts a spatial pattern of correlation between mooring M01 SSSA and the lagged (one month) upstream alongshore component of the geostrophic velocity anomaly. The correlation pattern is strongest along coastal Nova Scotia but also branches seaward along the 1000-m isobath suggesting some contribution from the shelf-edge current. NEC mooring N01 near-surface salinity shows only a marginal correlation with upstream currents (Figure 9d). This is partly explained by the complexity of NEC dynamics and the high variability of its thermohaline characteristics. Besides that, the mooring N01 correlation splits between the NSC

and the shelf-edge current, with a similar indication that both upstream current branches do impact NEC surface layer salinity (see also Figure 9b).

Next, we revisit Figure 4 satellite SSS data during the SMAP period (since mid-2015) and their relationship with SST, winds, and sea level. During this period, the M01 mooring salinity corresponds qualitatively with altimeter-derived NSC transport (Figure 8c). In particular, the 2018 salty event and 2019, 2020 fresh events are all accompanied by corresponding NSC deceleration (positive alongshore velocity anomaly) and acceleration (negative) events (Figure 8c). But, due to M01 measurement gaps, the 2016-17 fresh event (Figure 4d) is not captured in M01 records (Figure 8c), see also Figure 14c in Grodsky et al. (2018c). This illustrates that some of these coastal GoM water intrusions may go unobserved at this busy M01 location (see also Figure 11 below).

iv. Wind-GoM salinity links during the SMAP period

Combining results of Figures 7a and 4 (left and right panels in 4), it can be seen that the larger winter SSS anomalies of the last four winters, 2017-2020, qualitatively correspond with EOF1 of anomalous wind direction on the Scotian Shelf. Fresh conditions in Figures 4d and 4m correspond to weakened westerlies (downshelf wind anomalies) that accelerate the NSC (a stronger sea level high along seaward Nova Scotia) and its SSW transport (Figures 4f and 4o). The opposite effect, associated with enhanced westerlies, is observed in winter 2017-18 (Figures 4g and 4i). Not all events are solely associated with alongshore winds. In winter 2019 (Figures 4j and 4l), the fresh northeastern GoM and enhanced NSC are concurrent with offshore Scotian Shelf winds that accelerate a rightward Ekman transport (EOF2, Figure 7b). A more complex case is observed in the first SMAP winter (2015-16, Figure 4a) when weak eastern GoM SSSA results from the superposition of positive EOF2 (southeasterly wind anomaly, Figures 4c, 7) and weakly negative EOF1 (easterly winds off northern seaward Nova Scotia). These opposing factors may have canceled each other. Although sizeable SSS anomalies are observed during four out of five SMAP winters (Figure 4), only two of them are accompanied by distinct SST anomalies (Figures 4h, k). This implies that SSS may be a better indicator of GoM water inflow anomalies during winter periods when SST gradients can be reduced by air-sea interactions. Also, as seen in Figures 4 a-m and alluded to earlier, the NW location of Jordan Basin station

M01 may be sub-optimal for detecting eastern GoM salinity anomalies due to Cape Sable Inflow.

v. Eastern Gulf of Maine (eGoM) salinity index

The mapping capability of the SMAP satellite allows us to compute an area-wide anomaly index defined here as the monthly SSSA spatially-averaged over the eastern GoM (eGoM, see Figure 2a). Figure 10a shows that this eGoM index generally covaries with M01 SSSA but there are also significant periods of deviation. For example, it captures a fresh inflow event in late 2016 that is not observed at the M01 mooring. In winter (November-February), the temporal correlation between eGoM and M01 SSSA time series reaches $\text{CORR}=0.8_{0.54}^{0.91}$ (sub-indices hereafter show the 95% confidence range). The two time series also share similarly high correlations (~ 0.8) with NSCA. Although eGoM and M01 SSSA are highly correlated, Figure 4 suggests that the SMAP eGoM may be an improved indicator of CSI events, again because station M01 is frequently located on the periphery of SSSA due to NSC inflow.

The winter eGoM time series has a statistically significant correlation with Scotian Shelf winds spatially averaged over the NSC index area (Figures 10b and 10c, see Figure 2a for the area location). Based on five SMAP winters, its linear fit with previous month alongshelf (Ua) and cross-shelf (Uc) wind anomalies, $\text{eGoM} = 0.37_{0.16}^{0.57} \cdot Ua(t-1) + 0.14_{-0.02}^{0.30} \cdot Uc(t-1) + 0.02_{-0.14}^{0.19}$, is statistically significant at the 95% confidence level, with F -value, $F = 7.3 > 1$, and p -value, $p = 0.5\% < 5\%$. The eGoM index correlation with the previous month Ua is positive and reaches, $\text{CORR}=0.6_{0.21}^{0.82}$ (Figure 10b), with the 95% confidence interval not intersecting zero. After subtracting the Ua -correlated signal, $\Delta\text{SSSA} = \text{eGoM} - 0.37 \cdot Ua(t-1)$, the residual ΔSSSA has a weaker and only marginally significant correlation with previous month cross-shelf winds, $\text{CORR}=0.4_{-0.06}^{0.72}$ (Figure 10c). The utility of this eGoM index will be further assessed as the SMAP dataset lengthens.

f. Temporal-spatial assessment using POP2 ocean model data

To further assess the conclusions drawn above from the use of shorter period datasets and satellite-based observations, the next focus is on the results derived from the eddy-resolving 0.1° POP2 ocean model simulations detailed in section 2 (Figure 11). For consistency with the observation-based EOF analysis, the simulated monthly anomalous mixed layer current and salinity estimates along with atmospheric wind stress are decomposed using multivariate EOF

analysis over a 19-year-long model run that is forced by interannually varying winds and climatological river discharge. This implies that river discharge does not directly impact interannual variability in these simulations. To avoid possible impacts of strong current variance associated with Gulf Stream meanders on the EOF analysis, the EOF analysis domain excludes areas where the STD of sea level exceeds 6 cm. Results of Figure 11 show that, as for the observations, the southwesterly (alongshore) wind anomalies decelerate the NSC (Figure 11a), but accelerate fresh Gulf of St. Lawrence outflow along northeastern Cape Breton Island (refer to Figure 1 for geographic location names). In this model, the effect of NSC deceleration dominates and its resulting lower transport leads to higher salinity in a narrow coastal ribbon (< 50 km) along and seaward of Nova Scotia. This saltier water eventually enters the northeastern GoM through the Northern Channel and shallow areas adjacent to Cape Sable (Cape Sable inflow). This water inflow is also supported by decelerated in-Gulf currents along the southwestern side of Nova Scotia due to local onshore winds. This salty inflow continues cyclonically in the Maine Coastal Current and eventually down to the Mid Atlantic Bight. As noted earlier, the buoy M01 location (Figure 11a) is located near the westward edge of this northeastern GoM inflow salinity anomaly pattern.

Note also that Ekman transport associated with southwesterly winds shifts the position of the Shelf Slope Front to the right of wind direction, and thus induces a massive freshening in the southern part of the domain. Moreover, the Cabot Strait outflow along northeastern Cape Breton Island is accelerated (in line with the Ekman response to southwesterly winds) and thus accelerates freshwater transport out of the Gulf of St. Lawrence (see the vicinity of 46°N , 60°W in Figure 11a).

The second EOF mode of model simulations (Figure 11b) is associated with southeasterly (Nova Scotia onshore) winds. As in the observations (Figure 7), these simulations confirm that both along-shore and cross-shore winds impact along-shore currents on the Nova Scotia shelf. In comparison with the response to alongshore winds (Figure 11a), NSC deceleration occupies a wider coastal extent (~ 100 km) that may be more accurately resolved by altimeter-based and SMAP observations. This may explain why the analysis of Feng et al. (2016) based on altimeter-derived along-shore current (i.e. NSC) variability on the southwestern Scotian Shelf emphasizes the action of cross-shore winds. Southeasterly winds also decelerate the freshwater transport out of the Gulf of St. Lawrence along the northeastern coast of Cape Breton Island (Figure 11b) and

this may additionally reduce NSC freshwater transport. Simulations show that this reduced freshwater transport along Nova Scotia reaches the northeastern GoM where it circulates cyclonically in the Gulf interior (Figure 11b), but has a weaker impact on GoM salinity in comparison with the alongshore wind-induced EOF1 (Figure 11a). In part, this weaker inflow is explained by downwelling-favorable winds along southwestern Nova Scotia, and thus locally accelerated in-Gulf current along this coast that counteracts the effect of decelerated NSC.

4. Discussion and Summary

a. Local wind and basin-scale atmospheric variability

Due to larger spatial scales in the atmosphere, the correlations between GoM thermohaline variations and regional wind anomalies may be a part of broader teleconnections with Atlantic-wide atmospheric anomalies (e.g., Greene et al., 2013). At the basin scale, the atmosphere can elicit both near-immediate circulation response via wind-driven coastal dynamics (cf. Figures 8b, 8d and also Feng et al. (2016)), as well as at delayed time lags of months to years due to changes including shifts in Gulf Stream position and the subpolar polar gyre (Taylor and Stephens, 1998; Mountain, 2012). We focus here on correlations at zero lag. Using time series of mooring M01 salinity anomalies as the reference, the concurrent Atlantic winds and mean sea level pressure (MSLP) anomalies are composited for strong fresh and salty GoM episodes selected when the magnitude of the first vertical buoy salinity EOF exceeds half of its STD (PC1, Figure 5b). Figure 12a shows that strong winter GoM freshening coincides with a weakened Azores high and Icelandic low (Figure 12a). This MSLP anomaly pattern resembles an NAO mode (climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based), but it is also shifted south and west. This shift leads to a larger wind anomaly on the Scotian Shelf, accelerating the NSC and amplifying fresh/cold CSI transport into the GoM. Notably, this MSLP anomaly pattern time series does not always covary with the NAO index. For example, the NAO was close to neutral in winter 2004-05 when the strongest fresh GoM anomaly in past decades occurred.

Greene and Pershing (2003) found that the NAO and NW Atlantic shelf SSTA are positively correlated. This regional SST variation belongs to a larger scale pattern in which fresh conditions in the GoM are accompanied by cold SSTs extending across the NW Atlantic shelf and further into the subtropical Atlantic (Figure 12c). Along with warming across the subpolar gyre and

northern tropical Atlantic, the Atlantic-wide anomalous SST pattern resembles the classical tri-pole pattern of Xie and Tanimoto (1998). This is consistent with the negative wind anomaly seen in Figure 12a (weaker winds – warmer SST).

One important contrast that is highlighted when comparing Figure 12b to 12a is the lack of any apparent GoM-Scotian Shelf wind anomaly during periods of salty positive SSSA in the GoM. So while an NAO–, an increased winter wind forcing appears central to interannual GoM freshening, the opposite may not be true for NAO+. Instead, it is more likely that salty events are the result of advection of warmer salty Gulf Stream or slope water disturbances into the Gulf or onto the Scotian Shelf (Brooks, 1987; Lee and Brink, 2010; Grodsky et al., 2018b; Brickman et al., 2018). This mechanism is not directly wind-driven, nor it is a process known to preferentially occur in winter.

GoM salty and fresh episodes are related to a warmer and colder NW Atlantic shelf, respectively (Figure 12). Positively correlated T and S shelf anomalies (e.g., Loder et al., 2001; Flagg et al., 2006; Grodsky et al., 2017) are density compensated, which allows for salty anomalies to stay afloat and be detectable from space. Upper ocean anomaly trapping (Figure 4c) is corroborated by model analysis of GoM nitrogen flux (Zhang et al., 2019) highlighting the importance of shallow to intermediate depth inflow (5–75 m), at times exceeding the deep inflow (see also, Brickman et al., 2018). Similar to MSLP and wind anomaly composites (Figures 12a,b), SST composites are not symmetrical for salty and fresh GoM events. While the fresh episode SST composite involves pan-Atlantic SST anomalies (Figure 12c), the salty episode SSTA+ is limited to the shelf (Figure 12d). This suggests that shelf-slope exchanges due to eddy dynamics may play a larger role in forcing positive GOM SSSA periods.

b. Summary

New L-band satellite sea surface salinity (SSS) observations from the Soil Moisture Active Passive (SMAP) mission confirm the seasonal presence of significant winter period near-surface salinity variability in the northeastern Gulf of Maine (GoM). These wintertime satellite salinity observations are challenging because of weak L-band sensitivity to SSS change in cold water temperatures below 5°C that are common in the wintertime GoM. But accurate SMAP measurement of monthly ocean salinity anomalies is obtained (e.g., Figure 12) by applying a de-seasoning procedure that calculates SSS anomalies by subtracting the observed seasonal cycle at

each grid point. This procedure improves the accuracy of the residual anomalous SSS by removing the seasonally-dependent bias component along with the real seasonal cycle. Regional SMAP SSSA detection also benefits from the relatively large magnitude of winter SSS anomalies ($\sim 0.5 - 1$ psu). A multi-year analysis of these satellite SSSA data shows that larger anomalies are mostly confined to the northeastern GoM. Study results show that GoM salinity change is often associated with regional wind-driven ocean dynamics. Changes in Nova Scotia Current (NSC) inflow cause significant (~ 1 psu in amplitude) year-to-year variations in winter SSS in the northeastern GoM. Since 2015, three out of five winters of satellite SSS observations show the presence of such anomalies. These anomalies are confirmed by in-situ data from the M01 mooring in the interior GoM. Their origin is, in part, attributed to wind-induced changes in freshwater transport of the NSC. But, the observed buoy near-surface salinity anomalies correspond better to area-mean NSC variations averaged along seaward Nova Scotia coast rather than to winds. This suggests that additional factors contribute to NSC variability.

Alternative origins of salinity change at mooring M01 are addressed in Table 1 where zero-lag correlations between this salinity anomaly and several remote factors known to impact this shelf circulation. The highest correlation (~ 0.67) is found with the NSC geostrophic velocity anomaly derived from altimeter data (NSCA). Correlations with the Gulf Stream North Wall index (GSNW) and North Atlantic Oscillation index (NAO) have marginal values close to 0.2 (the 95% confidence level). Noticeably, the correlation with our estimate of the wind-driven component of NSC geostrophic velocity anomaly (NSCAw) is lower than for the total geostrophic velocity anomaly (NSCA). This suggests that the NSC velocity anomaly contains a sizeable component not driven by local instantaneous winds (cf. Han et al., 1997). Additional controls are briefly discussed in the Introduction with references to the Atlantic gyre response to large scale wind curl, which may affect the inner shelf circulation. These important relationships operate mostly on longer, multi-year periods through upstream impacts on the Nova Scotia shelf. The rich complexity of those impacts is beyond the scope of this study.

Results suggest that a wind-driven component impacts interannual NSC variability. Based on satellite altimetry and scatterometer winds, it is shown that NSC transport variability is influenced by variations from both alongshore and cross-shore wind components. Observation and model simulations show that northeasterly-to-northwesterly wind anomalies accelerate the NSC due to in-phase impacts of alongshore and cross-shore winds, and thus induce fresh

anomalies downstream in the northeastern GoM while wind anomalies from the opposite azimuth quadrant decelerate the NSC. Wind anomalies from the other two azimuth quadrants have a mixed impact on the NSC due to opposing impacts of alongshore and cross-shore wind stress components. Our findings related to these wind velocity components on NSC transport are confirmed by analysis of 0.1° global ocean model simulations. Simulation results also suggest that wind-induced modification of freshwater transport out of the Gulf of St. Lawrence may play an additional role in the GoM SSSA via a more remote upstream forcing (Han et al., 1997; Dever et al., 2016).

Despite wind anomalies that were similar to several previous years, winter 2018-19 sea level variations along coastal Nova Scotia (that define NSC to GoM transport) were significantly stronger. Although reasons for this recent NSC response amplification are not fully understood, the sign of year-to-year sea level change was consistent with corresponding wind changes. In winter 2017-18, the presence of a westerly-to-southwesterly wind anomaly resulted in a virtual disappearance of the Nova Scotia coastal sea level high and a significant reduction of the NSC. This relaxation partially contributed to the observed salty anomaly in the eastern GoM along with the unusual surface-trapped inflow of water WSW through the NEC (Grotsky et al., 2018b). In contrast to salty conditions in the winter of 2017-18, the next winter saw one of the strongest NSC accelerations during the SMAP period since 2015. The fresh northeastern GoM anomaly associated with this latter NSC acceleration event is captured by satellite SSS and is nicely depicted by in-situ data from the mooring M01 as a sudden, more than 1 psu, drop in upper 100m salinity that developed in late December 2018 and lasted through the middle of March 2019. SMAP also captures the fresh northeastern GoM SSSA of winter 2019-20 that also occurred concurrently with stronger than normal NSC.

SMAP SSS mapping since 2015 allows us to compute a candidate satellite-based index for GoM salinity change. This is defined here using monthly SSSA data averaged over the eastern GoM (eGoM) area off southwestern Nova Scotia. This area is most directly affected by the Cape Sable inflow. The eGOM has a high correlation with, but also deviations from the M01 SSSA. For example, it captures a fresh inflow event in late 2016 that is not observed at the M01 mooring. The index also has a statistically significant correlation with Scotian Shelf wind anomalies. Its further utility will be assessed as the SMAP SSS data record lengthens.

Study results assessing basin-scale impacts do agree, in part, with the others that find correlations between local hydrographic change along the US east coast and distant Atlantic locations that arise through NAO-like atmospheric patterns (e.g., Piecuch et al., 2019; Volkov et al., 2019). This research shows that periodic GoM winter freshening events are also concurrently linked with similar wind patterns. But the same is not completely true for positive salinity anomalies in the Gulf where salty episodes don't exhibit a similarly strong correlation with large scale Atlantic winds. This lack of correlation suggests that local concurrent zero-lag wind does not always impact NSC relaxation and, in turn, salt increase observed at GoM mooring M01; at least since 2003. Moreover, the most common pathway of salty water intrusion into the GoM is through its deepest open ocean boundary, the NE channel (Smith et al., 2012). This ingress, and its more complex circulation dynamics, is certain to impact M01 SSSA. A related mechanism discussed in the recent literature is shelf-slope interactions with salinity anomalies that are slowly propagating along the shelfbreak, and that eventually approach and entering the Gulf of Maine and St. Lawrence via the deeper channels (Brickman et al., 2018; Grodsky et al., 2018b). We thus conclude that eastern GoM freshening may be more dependent on and predictable by fall-to-winter wind anomalies on the Scotian Shelf, whereas positive SSSA events also require monitoring of longer-term and larger-scale slope sea T and S behavior upstream and near the NEC.

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Table 1. (top) Temporal correlation of 0–10m monthly salinity anomaly (SALTA) at mooring M01 with altimeter-derived Nova Scotia Current geostrophic velocity anomaly (NSCA), Gulf Stream North Wall index (GSNW), North Atlantic Oscillation index (NAO), and wind-driven component of NSC geostrophic velocity anomaly (NSCAw). (bottom) NSCA correlation with amplitudes (PC1, PC2) of two leading wind EOFs and NSCAw. M01 correlations exceeding their 95% significance level for magnitudes > 0.2 are shown in bold. NSC-wind correlations are based on longer time series since 1993 and are statistically significant for magnitudes > 0.15.

	NSCA	GSNW	NAO	PC1	PC2	NSCAw
SALTA@M01	0.66	0.24	0.19			0.35
	1mo	3mo	1mo			1mo
NSCA				0.3	0.25	0.39
				0mo	0mo	0mo

Figure 1. Gulf of Maine and adjacent region bathymetry (meter, blue shades). Scheme of two major inflow pathways: (greenish) fresh/cold inflow by the Nova Scotia Current, (reddish) warm/salty Northeast Channel inflow. Cyclonic Maine Coastal Current is sketched in gray. NERACOOS mooring location in Jordan Basin is shown.

Figure 2. Winter (DJF) and summer (JJA) climatologies for the Gulf of Maine and adjacent region. Shown are SMAP V4.0 sea surface salinity (SSS), altimeter geostrophic currents (black arrows, AVISO), and scatterometer winds (magenta arrows). In panel (a), Nova Scotia Current and eastern Gulf of Maine index areas are shown by the black box and lines, respectively. NERACOOS buoy M01 and N01 locations are shown in both panels.

Figure 3. Standard deviation (STD) of anomalous SSSA monthly sea surface salinity (SSSA) for (a) summer (JJA) and (b) winter (DJF) seasons. (c, d) Temporal correlation of SSSA with anomalous sea surface temperature (SSTA). Black contours in (a,b) are 100m and 1000m isobaths. Gulf Stream core (vertical hatching) is illustrated as maximum sea level variability area, $STD(SSHA) > 0.25\text{m}$, shelf-slope front (cross-hatching) is identified as maximum SSS variability area, $STD(SSSA) > 0.5\text{psu}$.

Figure 4. Winter (left) SSSA, (middle) SST anomaly, and (right) altimeter absolute dynamics topography (ADT) and scatterometer wind anomaly. For each winter, the month is selected based on the maximum SSSA (e.g., December 2016 for winter of 2016-17). Variables in the two left columns are shown for the current month (event peak), while the right column shows data for the previous month. Depth contours (100m and 1000m) are overlain. NERACOOS mooring M01 and N01 locations are shown in the left column.

Figure 5. (a) Time-depth diagram of monthly anomalous salinity (SALTA) from M01 mooring in the Gulf of Maine. (b) Time series of 0-50m averaged anomalous salinity and the first EOF amplitude (PC1) with half standard deviation of PC1 shown by horizontal dash lines. (c) Two leading vertical modes of buoy SALTA (numbers indicate the percentage of explained variance). (d) Seasonal magnitude (absolute values averaged for each calendar month) of 0-50m salinity anomaly and amplitudes of the two leading EOFs.

Figure 6. (a) Anomalous daily sea surface salinity (SSSA) from NERACOOS buoy M01 and collocated SMAP (against lhs y-axis) and SSS seasonal cycle (SSS seas, against rhs y-axis), anomalous (b) salinity (SALTA), and (c) de-trended temperature (TEMPA) versus depth from buoy M01 during SMAP observation period. In situ anomalies are calculated versus M01 record-long (2003-19) climatological cycles, SMAP SSSA is calculated versus the mission-long SSS climatology. Missing surface buoy data are filled with 20 –m data if mixed layer depth > 20 m.

Figure 7. Two leading multivariate EOFs of de-trended absolute dynamics topography and winds: (a, b) spatial patterns, (c) corresponding temporal principal components (PC), with Gulf of Maine salinity anomaly from buoy M01 (SALTA) included. Arrows in (c) show sample fresh events that are explained by negative PC1 episodes.

Figure 8. (a) Time series of Nova Scotia Current geostrophic velocity anomaly (NSCA, positive – northeastward) averaged over the Scotian Shelf index area (Fig. 2a) and its wind-driven component evaluated from the two leading EOF modes (Fig. 7, NSCA_w; b) their lagged correlation. (c) NSCA and 0-20m mean salinity anomaly (SALTA) from mooring M01, (d) their lagged correlation. Winter period (November-February) of each year is shaded grey in (a, c).

Figure 9. Lagged regression of NSCA with anomalous salinity (SALTA) at moorings (a) M01 and (b) N01, $\text{STD}(\text{NSCA})=0.015 \text{ m s}^{-1}$, 99% statistically significant correlations are hatched. Temporal correlation (TCORR) of 0-20m monthly-averaged (c) M01 and (d) N01 SALTA with previous month altimeter-derived alongshore geostrophic velocity anomaly elsewhere. Mooring locations are shown in (d). 100 and 1000-m depth contours are shown in (c, d).

Figure 10. (a) Monthly SMAP sea surface salinity anomaly (SSSA) averaged over the eastern GoM index area (eGoM, bars) and mooring site M01 SSSA. (b) Scatter plot of winter (November-February) eGoM SSSA against 1-month leading alongshore Nova Scotia wind anomaly, $Ua(t-1)$, and their linear regression fit. (c) A calculated residual

removing the alongshore fit, $\Delta SSSA = eGoM - 0.37 \cdot Ua(t-1)$, versus 1-month leading cross-shore wind anomaly. Small red open circles in (a) show months illustrated in Fig. 4.

Figure 11. The two leading modes of multivariate EOF analysis of surface salinity (shading), currents (black arrows), and wind stress (white arrows) based on POP2 eddy-resolving 19-year 0.1° global simulations driven by interannually varying atmospheric forcing and climatological river discharge. NERACOOS mooring M01 and N01 locations are shown. Depth contours (100m and 1000m) are shown in solid black.

Figure 12. Basin-scale surface atmospheric anomalies composited for winter months with strong (a,c) fresh or (b,d) salty SSSA at mooring M01. Top panels (a,b) show MSLP (shaded) and wind (arrows) anomaly composites. Bottom panels (c,d) show de-trended SST anomaly composites. Hatching illustrates Azores high and Icelandic low positions for (a) negative and (b) positive winter NAO. Black arrows in (a, b) correspond to areas where the temporal correlation of anomalous winds with mooring M01 SSSA is statistically significant at the 95% level. A strong SSSA event is defined as any month within the November-March period where $|SSSA|$ exceeds 50% of its STD.

Highlights

- SMAP detects significant eastern GoM SSSA (up to 1 psu) in four of five winters.
- Jordan basin SSSA correlation with Nova Scotia Current geostrophic anomaly is ~ 0.7 .
- Only half of the above correlation is explained by wind-driven current variations.
- Eastern GoM satellite SSSA index is better indicator of fresh Scotian Shelf inflows.