Interannual sea level variability in the western North Atlantic: Regional forcing and remote response

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[1] Annually averaged sea level (1970–2012) measured by tide gauges along the North American east coast is remarkably coherent over a 1700 km swath from Nova Scotia to North Carolina. Satellite altimetry (1993–2011) shows that this coherent interannual variability extends over the Middle Atlantic Bight, Gulf of Maine, and Scotian Shelf to the shelf break where there is a local minimum in sea level variance. Comparison with National Center for Environmental Prediction reanalysis winds suggests that a significant fraction of the detrended sea level variance is forced by the region's along-shelf wind stress. While interannual changes in sea level appear to be forced locally, altimetry suggests that the changes observed along the coast and over the shelf may influence the Gulf Stream path downstream of Cape Hatteras. **Citation:** Andres, M., G. G. Gawarkiewicz, and J. M. Toole (2013), Interannual sea level variability in the western North Atlantic: Regional forcing and remote response, *Geophys. Res. Lett.*, *40*, 5915–5919, doi:10.1002/2013GL058013.

1. Introduction

[2] Though average global sea level is rising [*Church and White*, 2011], this rise is not spatially uniform [e.g., *Stammer et al.*, 2013]. A region of particular concern is north of Cape Hatteras, North Carolina (Figure 1a) where the *rate* of sea level rise has increased by $3.80 \pm 1.06\,\mathrm{mm\,yr^{-1}}$ for 1990–2009 relative to that over the previous 20 years [*Sallenger et al.*, 2012]. Here the Gulf Stream, which carries warm waters poleward in the upper limb of the Atlantic Meridional Overturning Circulation (AMOC), leaves the coast and transitions from a western boundary current to a meandering free jet (Figure 2a), and the Deep Western Boundary Current, which carries cold fresh waters equatorward in the AMOC's lower limb across Line W [e.g., *Toole et al.*, 2011; *Peña-Molino and Joyce*, 2008], separates the meandering Gulf Stream from the wide shelf. Some cold fresh waters (so-called "Ford" waters) from the equatorward flowing Middle Atlantic Bight shelf and slope currents are entrained into the cyclonic side of the Gulf Stream [e.g., *Churchill and Gawarkiewicz*, 2012; *Gawarkiewicz et al.*, 2008; *Csanady and Hamilton*, 1988].

[3] It has been hypothesized that the recent acceleration in sea level rise north of Cape Hatteras is a regional response to changes in the large-scale North Atlantic circulation. For example, coastal sea level may respond to a slowing AMOC forced by changes in the density-driven circulation [*Yin et al.*, 2009]. Changes in Gulf Stream strength or position, resulting from changes in the wind-driven circulation related with the North Atlantic Oscillation (NAO), have also been proposed as drivers of the region's coastal sea level variability [*Ezer et al.*, 2013].

[4] To provide context for sea level rise rates, we report on the interannual sea level variations and examine the role of regional versus remote wind forcing at annual time scales. First, annually averaged sea level data from tide stations are used to identify a region of coherent interannual variability from the Scotian Shelf to Cape Hatteras. Then this variability (the "composite coastal sea level anomaly") is compared with basin-wide altimetry, winds, and the NAO index. The analysis suggests that winds over the shelf contribute significantly to interannual changes in coastal and shelf sea level and may have basin-wide impacts via deflection of the Gulf Stream near Cape Hatteras.

2. Data and Methods

[5] Tide gauge data are available from the Permanent Service for Mean Sea Level [*Woodworth and Player*, 2003]. Annually averaged relative sea levels were retrieved in April 2013 from the Revised Local Reference data set for 25 sites along the North American east coast from St. John's, Newfoundland to Key West, Florida (Figure 1a). Data are available through 2012, except for three stations whose records terminated at the end of 2011. Data gaps in a station's record between 1970 and 2012 are linearly interpolated, and the resulting 43 year time series at each station is used to calculate the station's linear trend. For five stations, the trends are calculated over a shorter period due to missing data at the beginning and/or end of the 43 year period.

[6] Delayed-time, monthly average mapped sea level anomalies (msla), which are gridded from multiple satellites and reported with 1/3° resolution, are produced by Ssalto/Duacs and available through Aviso from late 1992 through mid-2012. Using Aviso's monthly climatology, the annual cycle at each grid point is removed from the monthly msla. The residuals are then detrended and used to calculate annually averaged msla at each grid point in the North Atlantic from 1993–2011. Variance of the annually averaged msla in the North Atlantic is highest around the separated Gulf Stream. Northeast of Cape Hatteras, there is a narrow variance minimum along the shelf break—roughly coincident with the 100 m isobath—that separates this region of high variance from the variance on the shelf (Figure 2b).

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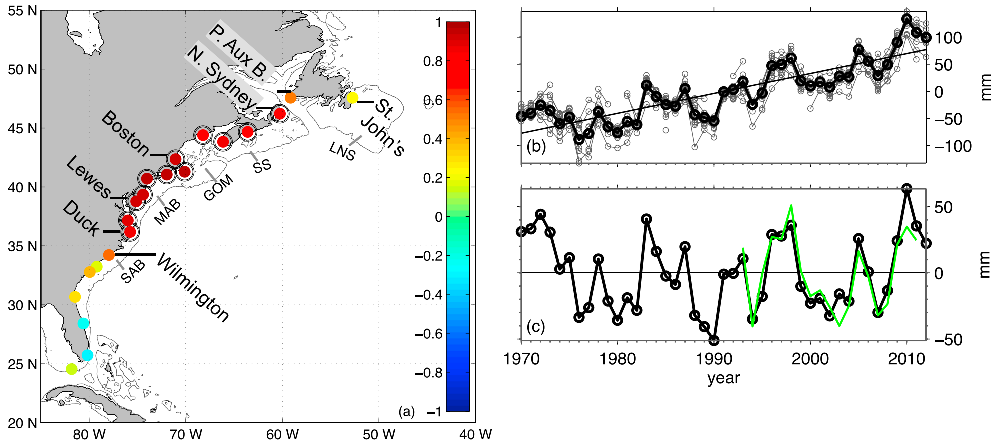

Figure 1. Annual average relative sea levels from tide stations. (a) Station locations; colors indicate r comparing individual station records (detrended) with the composite coastal sea level anomaly calculated from the circled stations. Southern Atlantic Bight (SAB), Middle Atlantic Bight (MAB), Gulf of Maine (GOM), Scotian Shelf (SS), Labrador-Newfoundland Shelf (LNS), and 200 m isobath are indicated. (b) The time series of the annual average composite sea level anomaly plus the trend (closed black circles) and individual station records from the 12 stations (open circles). (c) The detrended composite sea level anomaly (black) and satellite-derived msla from 72°W and 40.66°N (green).

[7] National Center for Environmental Prediction (NCEP) wind stress reanalysis data [*Kalnay et al*., 1996] are used to calculate annually averaged wind stress and wind stress curl. Though this has relatively coarse horizontal resolution (~2°), it is available over the entire period of interest here (1970–2012). The NAO index [*Hurrell*, 1995] represents anomalies in the sea level pressure distribution over the North Atlantic. Changes in NAO are associated with basin-wide changes in the strength and pattern of the large-scale wind field. Wintertime (January–March) NAO is calculated for each year from the monthly NAO.

[8] Analysis of annually averaged sea level records indicates that sea level is spatially coherent from 1970–2012 across the 12 stations located along the Middle Atlantic Bight, Gulf of Maine, and Scotian Shelf (Figure 1a). Within this region of coherent variability, the stations' linear trends

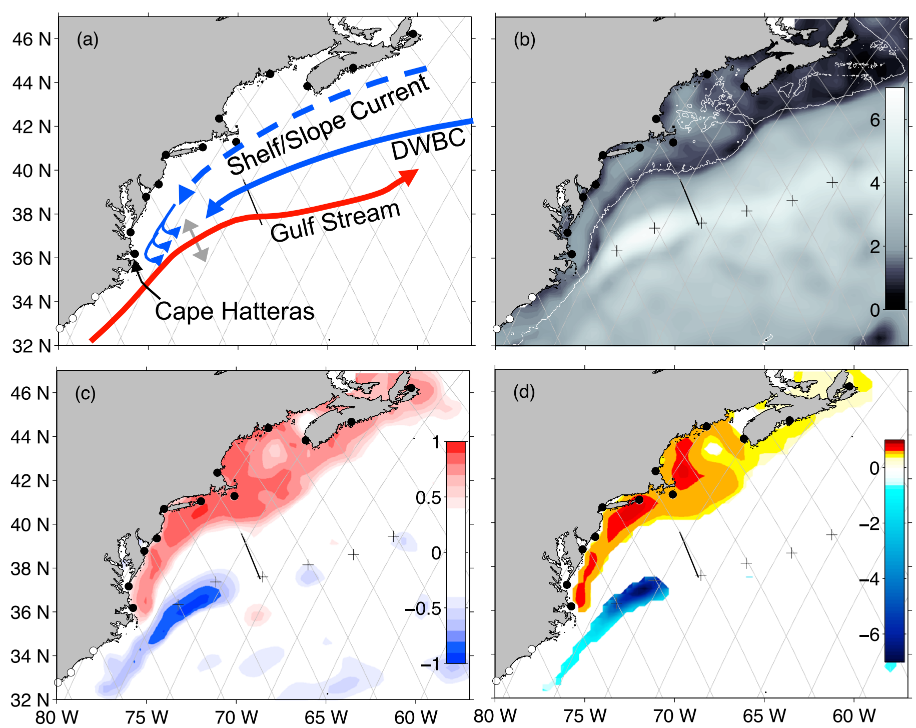

Figure 2. (a) Schematic of the surface circulation showing shelf/slope transport anomalies entrained into the Gulf Stream and Gulf Stream path variations. (b) Log of the variance in annually averaged msla. (c) Correlation and (d) regression between composite coastal sea level anomaly (see Figure 1c) and msla at each grid point. Shading in Figure 2c is shown only where Figure 2b has $|r| > 0.58$ (the 95% significance level for 10 effective degrees of freedom). Tide stations, 200 m isobath, and mean Gulf Stream position from *Peña-Molino and Joyce* [2008] (crosses) are shown as are satellite tracks and Line W (black line).

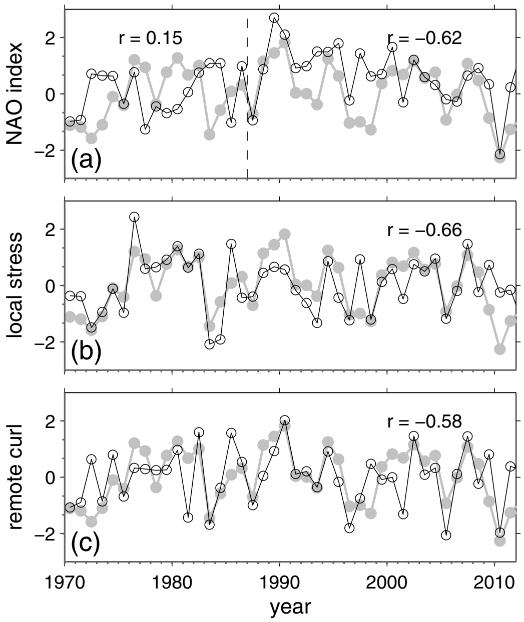

Figure 3. Comparison of $-1 \times$ composite coastal sea level anomaly (filled circles) with the following (open circles): (a) NAO index, (b) an example of along-shelf wind stress (see Figure 4b), and (c) an example of wind stress curl in the Labrador Sea near 51°W, 59°N (see Figure 4a). Note that the r values indicated on the plots are for the sea level without the flipped sign, and time series are normalized by their standard deviations.

range from 2.6 mm yr^{-1} to 5.0 mm yr^{-1} with no obvious pattern in the spatial distribution of the trends. The 12-station mean (i.e., the region's "composite coastal sea level trend") is 3.7 mm yr^{-1} (Figure 1b) with a standard deviation of 0.8 mm yr^{-1}. This rate of sea level rise is greater than the reported 1961–2009 global average, 1.9 ± 0.4 mm yr^{-1} [*Church and White*, 2011], consistent with previous studies which suggest that this region's sea level is rising faster than the global average [e.g., *Ezer et al*., 2013].

[9] To calculate a time series of annually averaged "composite coastal sea level anomaly", each station's sea level is first detrended as described above. For a given year, the residuals (Figure 1c, open circles) are then averaged across the 12 stations to give that year's composite sea level anomaly (Figure 1c, filled circles). For this calculation, missing station data are not interpolated and are excluded from a given year's average. In most years, 10 or more stations contribute to the calculation; the notable exception is 1994 when only five stations reported an annual average sea level. The resulting composite coastal sea level anomaly range is ±50 mm which is ~2/3 of the total sea level difference (160 mm) due to the linear trend from 1970 to 2012. Due to this strong interannual variability, the results presented below are not sensitive to the type of trend, linear versus quadratic, removed from the sea level record.

[10] Annually averaged sea level anomalies at the 12 stations are highly correlated with one another and with the composite coastal sea level anomaly (Figure 1a). Correlations between individual station records (detrended) and the composite are highest from Boston to Lewes ($r > 0.92$) but remain high near the edges of the region ($r = 0.85$ at Duck and $r = 0.79$ at North Sydney) before dropping off abruptly for stations outside of the region (e.g., $r = 0.55$ in Wilmington and $r = 0.51$ at Port Aux Basque). Correlations are significant at the 99% confidence level for $|r| > 0.53$ (for 1 year decorrelation scale and 21 effective degrees of freedom).

[11] Composite coastal sea level anomaly is significantly negatively correlated with wintertime NAO; however, this overall correlation is *entirely* due to the more recent period: for 1987–2012, $r = -0.62$, whereas prior to this (1970–1986), the correlation is not statistically different from zero (Figure 3a).

3. Discussion

[12] Comparison of the composite coastal sea level anomaly with satellite altimetry suggests that the annually averaged sea level varies coherently from the coast to the outer shelf. This is apparent in the correlation map (Figure 2c) in which the tide gauge-derived composite coastal sea level anomaly is compared with the satellite-derived msla at each altimetry grid point (1/3° resolution). Over the shelf, msla is strongly positively correlated with the composite coastal sea level anomaly (with 10 effective degrees of freedom from 1993–2011, the 99% significance level is 0.71): $r > 0.90$ in some locations and $r > 0.75$ over most of the shelf (the exception on the eastern Scotian Shelf is likely related to the shallow waters near the Sable Islands). As one example of this strong correlation, the satellite-derived msla from 72°W, 40.66°N (green line in Figure 1c) tracks the composite sea level anomaly closely ($r = 0.91$).

[13] Regression of composite coastal sea level anomaly on msla indicates that the amplitude of annually averaged sea level variations is largest at the coast and drops off toward the shelf break (Figure 2d), leading to annual variations in the sea surface gradient across the wide shelf. With sea level near the shelf break essentially "fixed" (recall the minimum in msla variance near the 100 m isobath, Figure 2b), the cross-shelf sea surface gradient is associated with variability in a cross-shelf pressure gradient. To first order, this is in geostrophic balance with an along-shelf current, and the associated transport variability, T, can be estimated by assuming barotropic (vertically uniform) along-shelf flow: $T = gH\Delta\eta/f$. Here g is the acceleration due to gravity (9.8 m s^{-2}), f is the local Coriolis parameter (9.4×10^{-5} s^{-1} at 40°N), H is the mean depth of a cross-shelf section, and $\Delta\eta$ is the variability in sea level difference across the shelf. For the southern Middle Atlantic Bight, $H \approx 30$ m and $\Delta\eta = \pm 50$ mm gives $T = \pm 0.16$ Sverdrup (Sv) where 1 Sv = 106 m^3 s^{-1} (for comparison, south of Cape Cod $H \approx 50$ m, giving $T = \pm 0.26$ Sv). This is a significant fraction of the reported mean equatorward shelf transport, 0.3 Sv [e.g., *Linder and Gawarkiewicz*, 1998], and suggests that in years with relatively high (low) coastal sea level anomaly, the equatorward shelf flow is enhanced (reduced).

[14] Outside of the shelf region, the correlations between msla and the composite coastal sea level anomaly are not significant with one notable exception. An 800 km band of strong negative correlation ($-0.61 > r > -0.84$) off Cape Hatteras is concentrated just southeast of the Gulf Stream's mean position [*Peña-Molino and Joyce*, 2008] on the anticyclonic side of the separated current. Regression coefficients here are an order of magnitude larger than over the shelf (Figure 2d) reaching -7, so the ±50 mm range in coastal sea level anomaly is accompanied by changes (of opposite sign) in sea level of ±350 mm. The magnitude and sign are

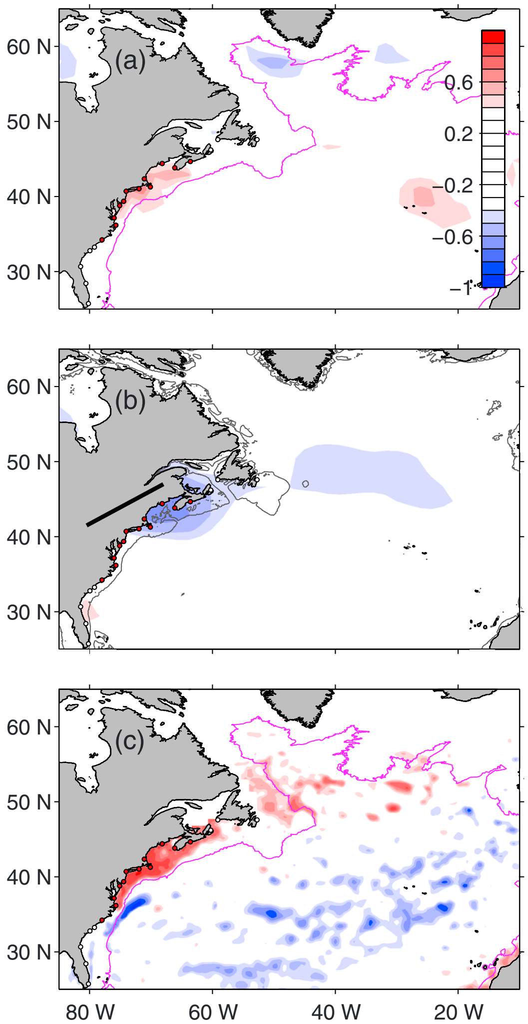

Figure 4. Correlation maps of composite coastal sea level anomaly and the following at each grid point: (a) wind stress curl, (b) along-shelf wind stress (toward 70°), and (c) msla. An *f*/*h* contour (magenta), 200 m isobath (grey), and along-shelf direction (heavy line in Figure 4b) are shown.

consistent with movements in the Gulf Stream path: For a 1 m sea level rise across a 100 km wide geostrophic current, changes of the local sea surface height of ±350 mm correspond to ±35 km shifts in the current axis position. Since mean sea level is lower on the Gulf Stream's onshore side, offshore shifts (onshore shifts) of the current are accompanied by a decrease (an increase) in sea level along the current's mean path.

[15] Downstream (i.e., east of 70°W) the correlation between composite coastal sea level anomaly and msla along the Gulf Stream is not significant. This is where the separated Gulf Stream begins to meander vigorously along its poleward route [see *Kelly et al.*, 2010, Figure 11], so the lack of correlation is not surprising. There are also no significant correlations between the composite coastal sea level anomaly and msla (Figure 4c) or detrended tide gauge observations (Figure 1a) southwest of the coast's bend near Cape Hatteras where the shelf is narrow, and the Gulf Stream—constrained by topography—flows close to the coast. With sea surface gradient serving as a proxy for Gulf Stream strength, this lack of correlation suggests that coast/shelf changes (at interannual timescales) observed north of Cape Hatteras are *not* driven by changes in the strength of the Gulf Stream arriving at Hatteras from the south. This result is not surprising, since the mean shelf/slope flow [*Zhang et al.*, 2011; *Lentz*, 2008; *Toole et al.*, 2011] and the propagation direction in the coastal waveguide all oppose northeastward penetration of signals beyond Cape Hatteras. However, this result does contrast with *Ezer et al.* [2013] who suggest sea level variability north of Cape Hatteras is due to changes in the strength of the Gulf Stream.

[16] Shelf sea level variability is likely influenced by a combination of local and remote forcing (with remotely forced signals reaching the shelf by wave propagation or advective processes). Though the NAO is often used as a proxy for the large-scale atmospheric forcing, the correlation between NAO and composite coastal sea level anomaly changes markedly around 1987 (Figure 3a), suggesting that the relationship between local and large-scale atmospheric forcing is not stationary. Hence, annually averaged, detrended wind stress curl and wind stress from NCEP are examined directly to assess which processes (local and/or remote) force the sea level variability on the shelf north of Cape Hatteras. These time series are compared with the composite coastal sea level anomalies from 1970–2012.

[17] Although annually averaged wind stress curl over the shelf is positively correlated with the composite coastal sea level anomaly (Figure 4a, red), this is not a likely driver of the shelf's sea level variability since the sign of the correlation is opposite to that expected from physical considerations (*positive* curl should cause the local sea level to *decrease* due to Ekman divergence). In contrast, wind stress along 70° (i.e., along shelf) over the shelf from ~40°N–50°N is negatively correlated with composite coastal sea level anomaly (Figures 4b (blue) and 3b), consistent with a mechanism where positive wind stress, which drives water off shelf due to the Ekman flow, causes a drop in the shelf's sea level, whereas negative wind stress piles water up against the coast due to the onshore Ekman flow. This mechanism is also consistent with the correlation drop between North Sydney and Port Aux Basque where the shelf orientation changes. Furthermore, though an along-shelf pressure gradient is important in setting the mean along-shelf flow in the region [*Zhang et al.*, 2011; *Lentz*, 2008], the magnitude of the varaiblity on the coast (±50 mm) is consistent with the range in the area-averaged along-shelf wind stress forcing (0.04 to 0.10 N m^{-2}) if one assumes a cross-stream geostrophic balance and an along-shelf frictional balance for the transport anomalies [*Sandstrom*, 1980] and appropriate frictional and length scale parameter values for the interannual variability over the shelf.

[18] This evidence for regional forcing by the along-shelf wind stress does not preclude a role for remote forcing. In fact, in the Labrador Sea, there are areas (e.g., near 51°W, 59°N) of significant negative correlation between wind stress curl and the composite coastal sea level anomaly (Figures 4a and 3c). However, a mechanism by which this remote signal propagates rapidly to the shelf is not clear from the satellite observations (Figure 4c).

4. Conclusions

[19] The range in annually averaged sea level variability (±50 mm) in this "hotspot" of sea level rise [*Sallenger et al.*, 2012] is large compared with the long-term trends (Figure 1),

so identifying changes in trends and establishing the underlying mechanisms remains challenging. At interannual time scales, local forcing (along-shelf wind stress) is an important driver of coast/shelf sea level variability (Figure 4b). Remote forcing may also be important (both at interannual time scales and at lower frequencies), but since the relationship between NAO and local wind stress varies (Figure 3a), using NAO as a proxy for atmospheric forcing may conflate the influences of local and remote forcing.

[20] Despite ambiguity regarding the role that remote forcing plays in driving interannual changes in the shelf's annually averaged sea level (e.g., via variations in Gulf Stream or AMOC strength or changes in the remote wind stress curl), altimetry illuminates (Figure 2) a connection between the coast/shelf and the large-scale circulation (i.e., the Gulf Stream path). If along-shelf transport anomalies (±0.16 Sv) cannot advect southward beyond Cape Hatteras (as suggested by the region of low correlations in Figures 1a and 4c), they are recirculated and entrained into the Gulf Stream, east of Cape Hatteras [e.g., *Churchill and Gawarkiewicz*, 2012; *Csanady and Hamilton*, 1988]. While it is unlikely that Gulf Stream path is directly influenced by the small transports of this entrained flow relative to the momentum of the Gulf Stream, perhaps these transport anomalies influence the potential vorticity structure and dynamics near the separation point. Since long duration observations with high horizontal and vertical resolution are not yet available from the separation region, it remains on open question whether interannual shelf variability causes variability in Gulf Stream position (rather than the reverse as postulated, for example, by *Ezer et al*. [2013]). Interpreting Gulf Stream position as a response, rather than a driver of slope and shelf variability, is not without precedent; *Peña-Molino and Joyce* [2008] report that changes in slope waters flowing southwestward across Line W toward the separation point between the 1000 m and 3500 m isobaths lead to changes in Gulf Stream path.

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