Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast

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[1] Recent studies indicate that the rates of sea level rise (SLR) along the U.S. mid-Atlantic coast have accelerated in recent decades, possibly due to a slowdown of the Atlantic Meridional Overturning Circulation (AMOC) and its upper branch, the Gulf Stream (GS). We analyzed the GS elevation gradient obtained from altimeter data, the Florida Current transport obtained from cable measurements, the North Atlantic Oscillation (NAO) index, and coastal sea level obtained from 10 tide gauge stations in the Chesapeake Bay and the mid-Atlantic coast. An Empirical Mode Decomposition/Hilbert-Huang Transformation (EMD/HHT) method was used to separate long-term trends from oscillating modes. The coastal sea level variations were found to be strongly influenced by variations in the GS on timescales ranging from a few months to decades. It appears that the GS has shifted from a 6–8 year oscillation cycle to a continuous weakening trend since about 2004 and that this trend may be responsible for recent acceleration in local SLR. The correlation between long-term changes in the coastal sea level and changes in the GS strength was extremely high ($R = -0.85$ with more than 99.99% confidence that the correlation is not zero). The impact of the GS on SLR rates over the past decade seems to be larger in the southern portion of the mid-Atlantic Bight near Cape Hatteras and is reduced northward along the coast. The study suggests that regional coastal sea level rise projections due to climate change must take into account the impact of spatial changes in ocean dynamics.

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1. Introduction

[2] Several recent studies [*Boon*, 2012; *Ezer and Corlett*, 2012a, 2012b; *Sallenger et al.*, 2012], using different analysis methods, indicate that the rates of sea level rise (SLR) have been accelerating along the coastal mid-Atlantic region (the so-called "hot spot" of accelerated SLR, as referred to by *Sallenger et al.*). The SLR rate and the SLR acceleration in this region are significantly higher than those found in the global ocean [*Holgate*, 2007; *Church and White*, 2011; *Houston and Dean*, 2011; *Church et al.*, 2011], although there are still some disagreements between different studies on the way to calculate trends in sea level data [*Baart et al.*, 2012]. The acceleration is especially evident in coastal locations north of the separation point of the Gulf Stream (GS) from the coast at Cape Hatteras but is much smaller or not significant along the southeast coast south of Cape Hatteras [*Boon*, 2012]. As a result, low-lying coastal communities in the mid-Atlantic region, such as the Hampton Roads area in the Chesapeake Bay (CB), have seen a significant increase in the frequency of flooding in recent years [*Mitchell et al.*, 2013]. The high rate of relative SLR in the CB (2–3 times faster than the global mean SLR) has been attributed in the past to local land subsidence [*Boon et al.*, 2010]. However, subsidence due to long-term post glacial rebound [*Tamisiea and Mitrovica*, 2011] is a slow process that cannot explain fast changes of SLR rates in recent years. The SLR acceleration and its spatial location suggest that ocean dynamics is the more likely forcing mechanism behind the recent acceleration [*Levermann et al.*, 2005; *Sallenger et al.*, 2012; *Ezer and Corlett*, 2012a]. The hypothesis behind the "dynamic sea level change" is that variations in the Gulf Stream (GS) location (Figure 1) and strength will change the sea surface height gradient across the GS (Figure 2) and, in turn, the sea level on both sides of the Stream. The northeastward flowing GS is roughly in a geostrophic balance with ~1–1.5 m difference (over a distance of ~100 km) in elevation between the lower elevation along the coast, northwest of the GS, and the higher elevation southeast of the GS (Figure 2). This elevation gradient is proportional to the surface velocity of the GS, so weakening of the GS strength will raise the sea level northwest of the GS (along the U.S. East Coast) and lower the sea level southeast of the GS (in the open sea, where it should not be of much a concern). As an example, altimeter data across

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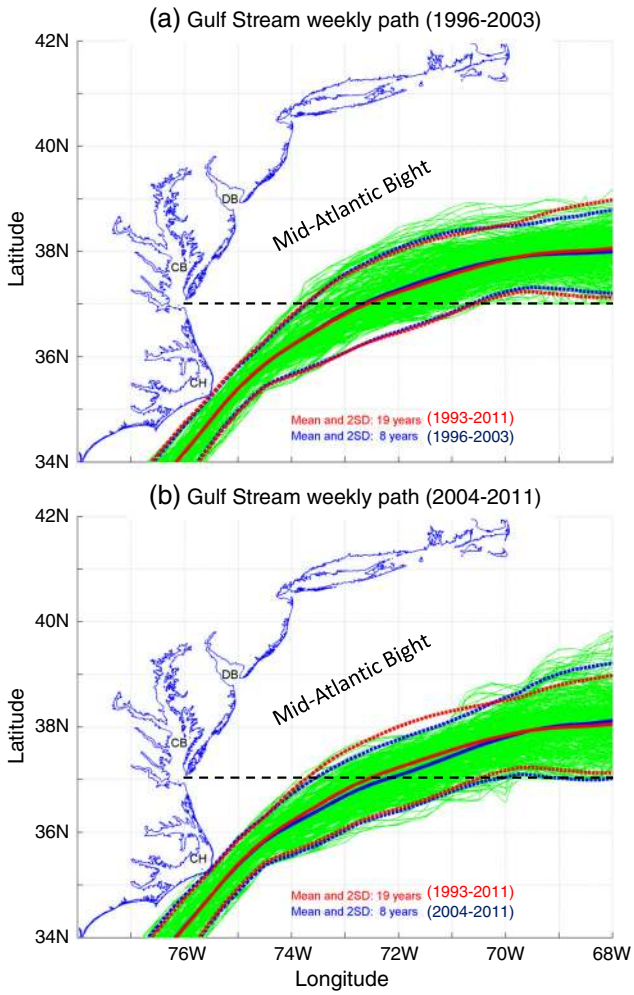

Figure 1. Green lines are the locations of the Gulf Stream front obtained from weekly altimeter data. The front is calculated from the maximum elevation gradient normal to the Gulf Stream for (a) 1996–2003 and (b) 2004–2011. The heavy red lines (identical in Figures 1a and 1b) are the mean and 2 standard deviations of the entire record (1993–2011), while blue lines are for each 8 year period. The locations of the Chesapeake Bay (CB) and the Delaware Bay (DB) are indicated. The black dash line across 37°N is the location of the cross section shown in Figure 2 from the CB to the GS.

37°N (Figure 2) show that the coastal sea level near the mouth of the CB was about 12 cm higher in September 2011 compared with that in September 2000. In 2000, the GS flow was stronger (i.e., larger elevation slope) and closer to the coast (at ~73°W), while during the latter period, the GS was weaker and farther offshore (69°W–71°W). When the GS was farther offshore, there is a more significant downward sea level slope between 72°W and 75°W, suggesting a stronger southward Slope Current [*Csanady and Hamilton*, 1988]; the Slope Current may have also contributed to the increased coastal sea level in 2011. Note that the 12 cm change in coastal sea level shown in Figure 2 between 2000 and 2011 is 3 times larger than the average local SLR (~4 cm/10 yr; *Boon et al.*, 2010, *Ezer and Corlett*, 2012a) and 6 times larger than the global SLR over the twentieth century (~2 cm/10 yr; *Holgate*, 2007).

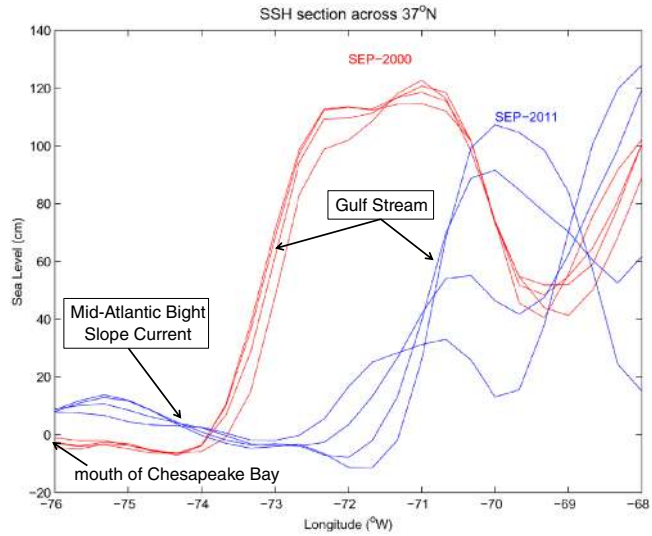

Figure 2. Examples of Sea Surface Height (SSH) at weekly intervals across 37°N (see Figure 1) obtained from altimeter data. Red and blue lines are from September 2000 and September 2011, respectively. The northward flowing Gulf Stream and the southward flowing Slope Current are shown.

[3] The idea that variations in the GS can impact coastal sea level has been suggested by observations [*Sweet et al.*, 2009] and by circulation models of the Atlantic Ocean [*Ezer*, 1999, 2001a, 2001b] and by global climate models [*Yin et al.*, 2009]. For example, *Ezer*, [2001a] found a significant correlation on decadal timescales between the transport of the Gulf Stream and the coastal sea level, whereas a reduction of ~1 Sv (10^6 m^3 s^{-1}) in the model GS transport induced ~1 cm coastal sea level rise along the U.S. East Coast, west of the GS. On the other hand, south and east of the GS, a weaker GS such as seen around 1970 coincides with anomalous low sea level in Bermuda [*Ezer*, 1999]. Idealized model simulations demonstrate that future warming of polar regions would cause weakening of the GS and sea level rise that is 2–3 times larger along the western side of the North Atlantic (i.e., the U.S. East Coast) than that expected along the eastern side of the North Atlantic (i.e., the European coasts) [see *Ezer*, 2001b, Figure 9]. The above results motivated this study, which is aimed to see if data can confirm the relation between the GS and the coastal sea level, as found in models. Various studies suggest that climatic changes such as the warming and freshening (due to melting ice) of the subpolar North Atlantic may reduce sinking of dense waters in high latitudes and slow down the Atlantic Meridional Overturning Circulation (AMOC) [*Ezer* 2001b; *Sallenger et al.*, 2012; *McCarthy et al.*, 2012; *Srokosz et al.*, 2012]. Changes in the AMOC are likely to impact the transport of the GS (the upper northward branch of the AMOC). The question is whether or not these changes are detectable in the sea level gradient across the Gulf Stream or in the local coastal sea level data. The AMOC and the GS are also affected by interannual and decadal variations associated with large-scale variations in the atmospheric pressure and wind patterns over the North Atlantic; these variations can be characterized by the North Atlantic Oscillations (NAO) index. In fact, the transport of the Florida Current at 27°N, which feeds the GS, was found to be significantly anticorrelated with the NAO

index [*Baringer and Larsen*, 2001], although the relation between NAO and the GS may be less obvious in recent years [*Meinen et al*., 2010].

[4] One of the challenges in analysis of sea level data is how to separate the long-term trend from the higher-frequency variability of the many different timescales involved. For example, standard curve-fitting and filtering methods would have difficulties separating the sea level trend from long-term variations such as the global 60-year oscillation cycle [*Chambers et al*., 2012]. This difficulty led to the development of a new analysis method for sea level [*Ezer and Corlett*, 2012a, 2012b], which can remove high-frequency oscillations as well as cycles with long periods that are comparable to the record length itself. We will consider in this study scales ranging from a few months to decadal and long-term climate-scale trends. The analysis method is based on Empirical Mode Decomposition (EMD)/Hilbert-Huang Transformation (HHT) [*Huang et al*., 1998; *Wu and Huang*, 2004; *Wu et al*., 2007; *Huang and Wu*, 2008]; to the best of our knowledge, the EMD/HHT method has not been used for analyzing sea level trend before it was introduced by *Ezer and Corlett* [2012a, 2012b]. *Ezer and Corlett* used 5000 bootstrap simulations [*Mudelsee*, 2010], i.e., randomly resampling the data itself, to calculate confidence intervals, and show that the SLR trends obtained from the EMD/HHT analysis are accurate within about $\pm 0.5\,\mathrm{mm\,yr^{-1}}$ with 95% confidence level. Note that using standard curve-fitting methods, sea level records of at least 60-year are usually required to achieve the same confidence level [*Douglas*, 2001; *Boon et al*., 2010], while the bootstrap calculations allows analysis of shorter records. The EMD/HHT method is especially useful for non stationary and nonlinear time series, and has been used for different geophysical applications [*Huang and Wu*, 2008], such as earthquakes, hydrological and atmospheric data [*Rao and Hsu*, 2008] and intercomparisons between climate models [*Chen et al*., 2012]. The method decomposes any time series data into a finite number of intrinsic mode functions with time-variable amplitudes and frequencies; the number of modes is determined by the length of the record and the intrinsic variability of the time series [*Wu and Huang*, 2004]. The method is nonparametric, so the calculated trends can take any shape. The HHT-calculated SLR trends and acceleration in the CB compared very well with results obtained from standard curve fitting methods [*Ezer and Corlett*, 2012a]. The method was also used to calculate future projections of local SLR based on extrapolation of past SLR rates and acceleration [*Ezer and Corlett*, 2012b]; other global SLR projections are often based on climate numerical models [*Schaeffer et al*., 2012].

[5] This paper is organized as follows. First, in section 2, the data and the analysis method are described; then, in section 3, the results are presented; and, finally, in section 4, discussions and conclusions are offered.

2. Data and Analysis Methods

[6] Monthly mean sea level records from 10 tide gauge stations (7 in the CB and 3 along the Atlantic coast) were obtained from NOAA's "verified data" (http://tidesandcurrents.noaa.gov/). The CB stations (same as in *Ezer and Corlett*, 2012a, 2012b) are spread from the city of Norfolk, VA, (Sewells Point) in the south to Baltimore, MD, in the north and along the Atlantic coast from Duck, NC, in the south to Atlantic City, NJ, in the north (Figure 3). Record length ranges from three stations with relatively short records of 25–37 years (Duck; Chesapeake Bay Bridge Tunnel, CBBT; Lewisetta) to two stations with relatively long records of over 100 years (Atlantic City and Baltimore). Most of these stations have been used in previous studies of SLR [*Boon et al*., 2010; *Boon*, 2012; *Ezer and Corlett*, 2012a, 2012b; *Sallenger et al*., 2012]. The sea level data spread over a large geographical distance, so one has to distinguish between local and large-scale impacts. For example, *Boon et al*. [2010] estimated that the land subsidence in the CB ranges between ~$1.3\,\mathrm{mm\,yr^{-1}}$ in the upper bay at Baltimore to ~$4\,\mathrm{mm\,yr^{-1}}$ in the lower bay at CBBT, and there are spatial differences in the local tidal dynamics, local wind pattern, river runoffs, etc. To detect any large-scale influence from the Atlantic Ocean on coastal sea level, one needs to search for coherent signals that impact the majority of the tide gauge stations.

[7] The monthly Florida Current transport from cable measurements across the Florida Strait at 27°N [*Baringer and Larsen*, 2001; *Meinen et al*., 2010; *McCarthy et al*., 2012] is obtained from the NOAA/Atlantic Oceanographic and Meteorological Laboratory website (www.aoml.noaa.gov/phod/floridacurrent/); the data include the periods 1982–1998 and 2000–2012 with a gap of 2 years. We also obtained from NOAA/Climate Prediction Center (http://www.cpc.ncep.noaa.gov/) the monthly North Atlantic Oscillation (NAO) index, representing the large-scale oscillations in the atmospheric pressure difference between the Icelandic low and the Azores high. Previous studies show that the NAO index is anticorrelated with variations of the Florida Current transport at 27°N [*Baringer and Larsen*, 2001], so we tested here the possible correlation of the NAO with the GS upstream of the Florida Strait, north of 35°N.

[8] The altimeter data for the GS region were obtained from the AVISO website (http://www.aviso.oceanobs.com/). The composite of absolute sea surface height (SSH) derived from several satellites is provided on a $0.25° \times 0.25°$ grid and on a weekly basis. The location with the largest SSH gradient perpendicular to the GS flow direction (representing the maximum surface geostrophic velocity) was searched in order to identify the GS front (Figure 1). Then, the average SSH gradient across the GS (in meter elevation change per 100 km horizontal distance) over the region 70°W–75.5°W (the Mid-Atlantic Bight, north of Cape Hatteras) was calculated to produce a time series of average monthly gradient for 1993–2011. The chosen region roughly covers the longitudes of the so-called "hot spot" of accelerating SLR [*Sallenger et al*., 2012]. It is assumed that these SSH gradient data represent the average strength of the GS. These data were also used to test whether or not the GS gradient is related to the transport measured upstream in the Florida Strait.

[9] The time series of monthly GS data and sea level in the CB were analyzed in two ways. The first method was a standard spectral analysis and coherency; this method is useful for finding periodic oscillations with fixed frequencies, but since altimeter data are available for only ~18 years, only oscillations with periods ranging from a few months to about 5 years can be detected. To study longer-term

Figure 3. The location of tide gauge stations used in this study; seven stations are located in the Chesapeake Bay and three along the Atlantic coast. The starting years of the records used are indicated in the inset.

variations from interannual scales longer than ~5 years to decadal variations and climate-related trends, the EMD/HHT analysis method demonstrated by *Ezer and Corlett* [2012a] was used. The Empirical Mode Decomposition/Hilbert-Huang Transform [*Huang et al.*, 1998] is a nonparametric, nonstationary analysis, whereas a time series is decomposed into a finite number of intrinsic oscillatory modes using the local maxima or minima envelope. Oscillatory modes with periods that are too long (relative to the record length) to be recognized by spectral analysis methods can still be identified by the EMD/HHT analysis. After all the oscillating modes are removed, the remaining nonoscillating last mode is the trend [see *Ezer and Corlett*, 2012a, 2012b, for details]. The definition of the trend in the EMD/HHT calculation is "a time-dependent function with at most one extremum representing either a mean trend or a constant" [*Wu et al.*, 2007; *Chen et al.*, 2012], so any mode function that includes at least two extrema (e.g., an incomplete long cycle with one minimum and one maximum) is not considered by the HHT as part of the trend. Therefore, comparing our analysis to standard filtering and curve fitting methods may result in slightly different trends, whereas, for example, the SLR trends in *Boon* [2012] and *Sallenger et al.* [2012] seem to include the 60 year cycle [*Chambers et al.*, 2012], while the HHT analysis removes this cycle from the trend.

[10] Figures 4–6 show the HHT analysis of the sea level in Baltimore (the longest of the sea level records), the average GS gradient, and the NAO, respectively. Mode 0 is the original monthly data set, and the last mode is the trend. The intrinsic mode functions represent oscillatory cycles with decreasing frequency, but within each mode, the frequency can be time dependent and not restricted to any particular frequency as in spectral methods. The value of the HHT is that it can remove from the trend even long incomplete cycles, so, for example, mode 8 of the sea level data (lower left panel in Figure 4) and mode 8 of the NAO

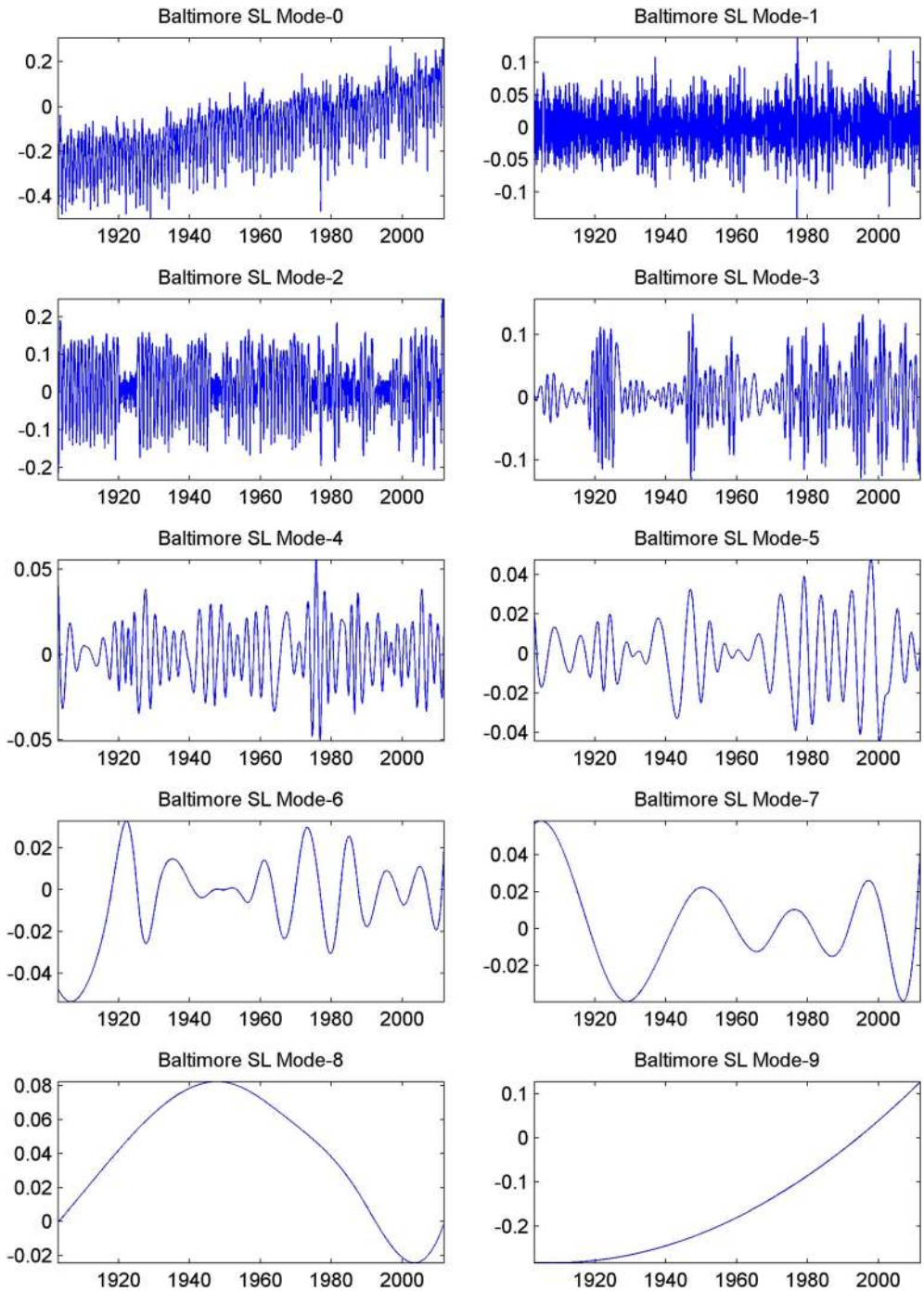

Figure 4. The amplitude (in m) of the EMD/HHT modes of the sea level in Baltimore. Mode 0 is the original monthly data, modes 1–8 are the oscillating modes, and mode 9 is the remaining trend.

(lower left panel in Figure 5), both seem to show a 60 year cycle (but in opposite phase), that may be related to the global 60 year cycle discussed by *Chambers et al*. [2012]. Standard filtering methods will not be able to remove a 60 year cycle from a 100 year record, giving instead the impression of an SLR deceleration from 1950 to 1990 before the acceleration of recent decades started [see *Boon*, 2012, Figure 2]. The last mode (the trend in Figure 4) shows, in Baltimore, an average upward acceleration of SLR of 0.076 mm yr^{-2} [*Ezer and Corlett*, 2012a] for 1902–2011, which is larger than the acceleration of 0.044 mm yr^{-2} calculated by *Sallenger et al*. [2012] for 1950–2009 and lower than the acceleration of 0.166 mm yr^{-2} calculated by *Boon* [2012] for 1969–2011. Note that calculations of mean SLR rates or SLR acceleration with HHT do not involve fitting linear or quadratic functions to the data, as done in other studies [*Church and White*, 2011; *Boon*, 2012; *Sallenger et al*., 2012], instead, rates are calculated from simple averaging of the instantaneous slope (SLR rate) or monthly change in slope (acceleration) of the trend line. The trends in the average GS strength and in the NAO, both show apparent decline in recent years. The GS record is much shorter than the sea level records, so one cannot say

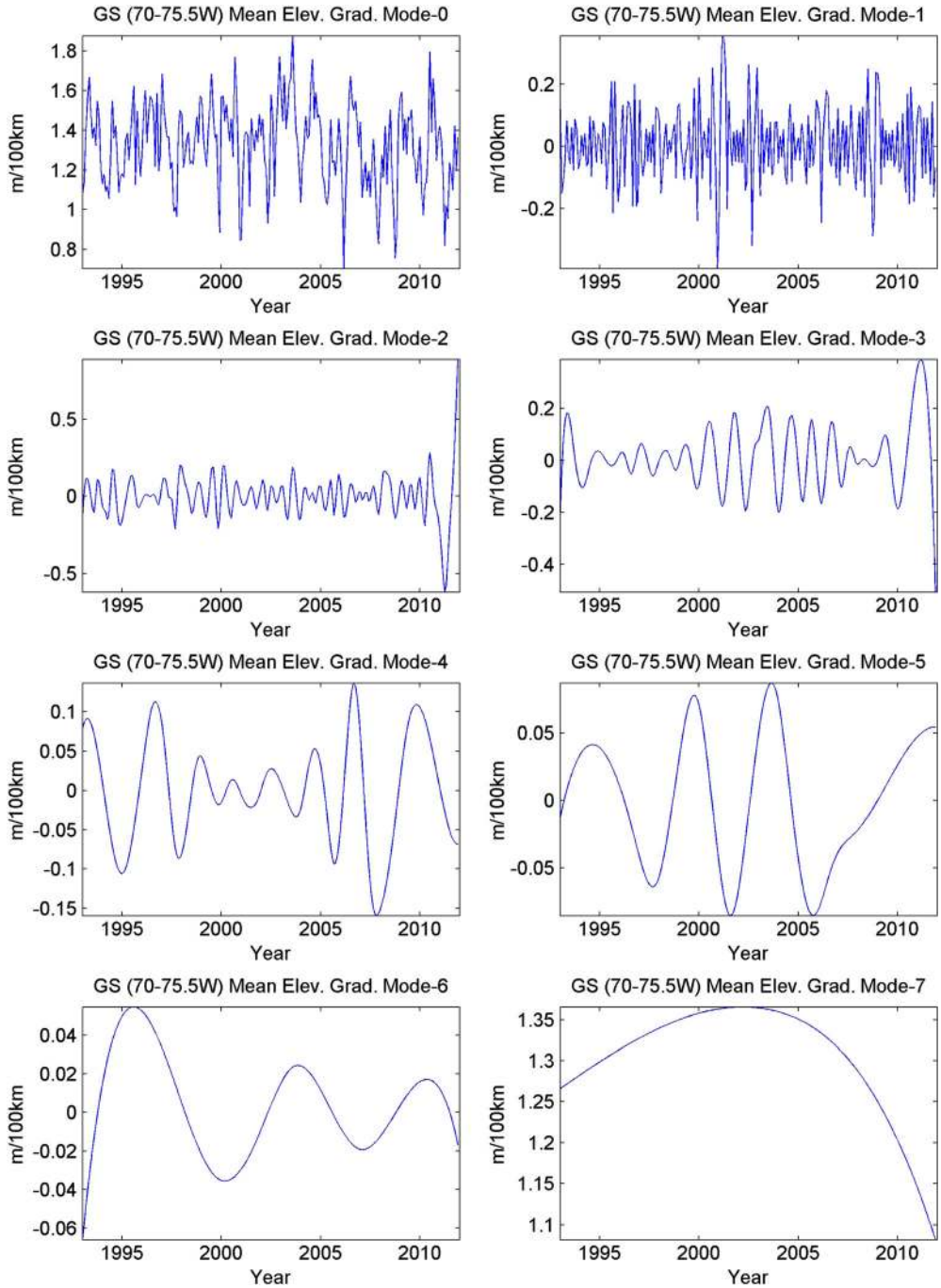

Figure 5. The amplitude of the EMD/HHT modes of the Gulf Stream average gradient between 70°W and 75.5°W. Mode 0 is the original monthly data, and mode 7 is the remaining trend after the six oscillating modes have been removed from the original data.

for sure that this trend does not include some unresolved long-term cycles. Nevertheless, the comparisons between the GS gradient record, the Florida Current data, and the sea level data (shown later) suggest that this trend is real.

3. Results

3.1. Intraannual to Interannual Variations in the NAO, the Gulf Stream, and the Coastal Sea Level

[11] Several studies looked at the relation between the Florida Current transport and the NAO [*Baringer and Larsen*, 2001; *Meinen et al*., 2010]. Therefore, we tested whether or not the GS gradient is also affected by the NAO. Figure 7 shows the spectra and coherence between the GS gradient and the NAO. The two time series are coherent at 1–2 year timescales, and they are in opposite phase, similar to the results of [*Baringer and Larsen*, 2001]. There are also coherence values at intraannual frequencies of periods of a few months, but the meaning of high-frequency variations in the NAO is not clear, so they are not discussed here. The spectra of both the NAO and the GS have peaks at ~5 year period (57 months), but the GS record is not long

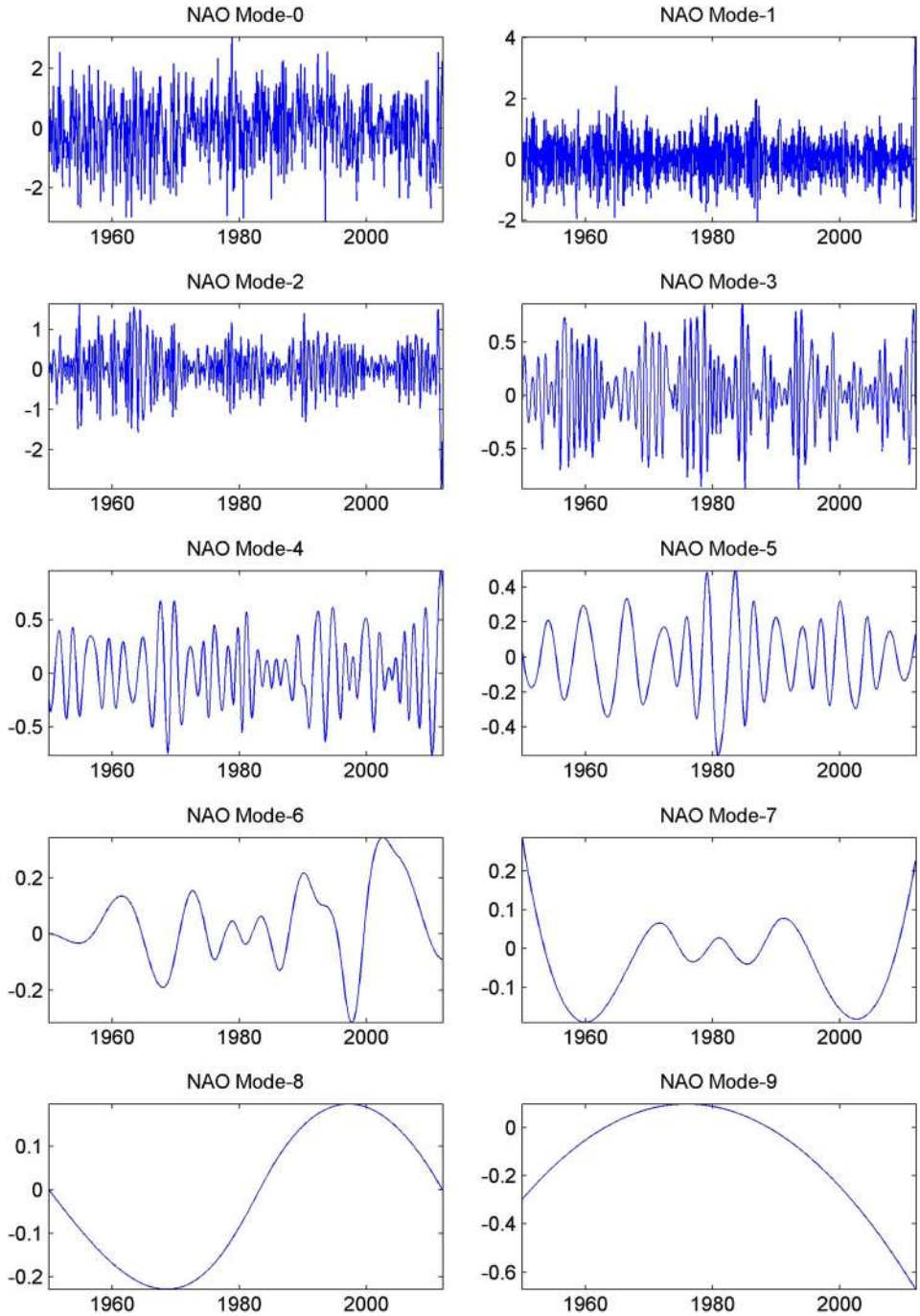

Figure 6. The amplitude of the EMD/HHT modes of the NAO index average. Mode 0 is the original monthly data, and mode 9 is the remaining trend after the eight oscillating modes have been removed from the original data.

enough to show significant coherence values at long periods, so HHT analysis of the GS will be discussed later to look at longer timescales.

[12] Next, in Figure 8, the spectrum of the GS gradient is compared with the spectrum of sea level data. All the seven tide gauge records of the CB show very similar spectrum results for monthly data, so the spectrum of only one station, Baltimore, at the northern edge of the CB (Figure 3) is shown in Figure 8 (the time series itself is shown in the upper left panel in Figure 4). Both the GS and the coastal sea level show energetic peaks at similar periods of 5–6, 9–10, and ~57 months; the 5–6 and 9–10 month peaks are significant (the gray area represents the 95% significance interval), and the two time series are coherent at several bands, from periods of a few months to about 1 year. The record length is not long enough to show significant coherence at the longer, 57 month peak. Peaks at about 1 and 2 years are also found in both records: the peaks are less significant in the sea level data, but they are coherent with the GS and out of phase (~180° difference for most peaks).

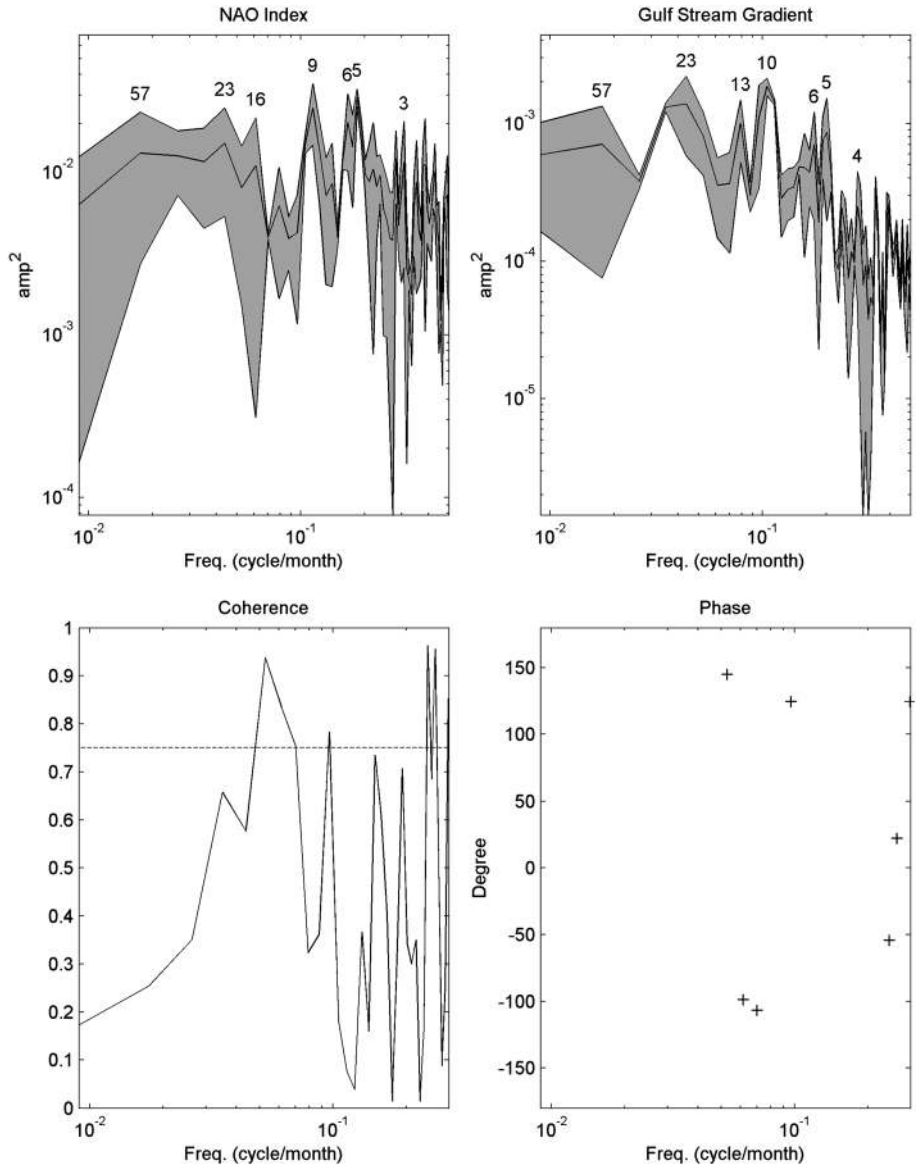

Figure 7. (top) Power spectra of (left) the NAO index and (right) the Gulf Stream gradient (in m^2); 95% confidence intervals are shown in gray, and periods of peaks (in months) are indicated by numbers. (bottom) (left) Coherence and (right) phase difference between the two time series; phase is shown for periods with coherence values above 95% significance (horizontal dash line).

The latest anticorrelation is consistent with the hypothesis that a weakening GS is related to a higher coastal sea level, as discussed before, and the fact that for almost every peak in the sea level record there is a peak in the GS record indicates that variations in the monthly sea level are largely driven by GS fluctuations, even for a location such as Baltimore, that is so far from the GS. It is also interesting to note that both the NAO index and the GS gradient show significant peaks near the annual and biannual periods. Seasonal variations in the Florida Current have been shown before [*Meinen et al*., 2010], whereas larger transport is often observed during the summer. *Meinen et al*. [2010] also showed that most of the total variability of the daily Florida Current transport is in high frequency (as much as 70% of the variability is in periods shorter than 11 months), so identifying decadal and longer variability in the data using standard spectral analysis methods is not possible without much longer records. To overcome the limitations of spectral analysis in resolving oscillations with long periods, results from the EMD/HHT analysis are discussed next.

3.2. The Impact of Decadal and Climatic Changes in the Gulf Stream on Coastal Sea Level

[13] *Ezer* [2001a] showed that in an Atlantic Ocean numerical model, decadal variations in the GS transport are highly correlated with variations in coastal sea level, but can this relation be seen in observations? Based on limited data of a few months, *Sweet et al*. [2009] suggested that such correlation in fact exists and that a weakening of the GS may explain the unusually high water levels observed during the summer of 2009. The GS elevation gradient represents the strength of the surface current after the GS has separated from the coast,

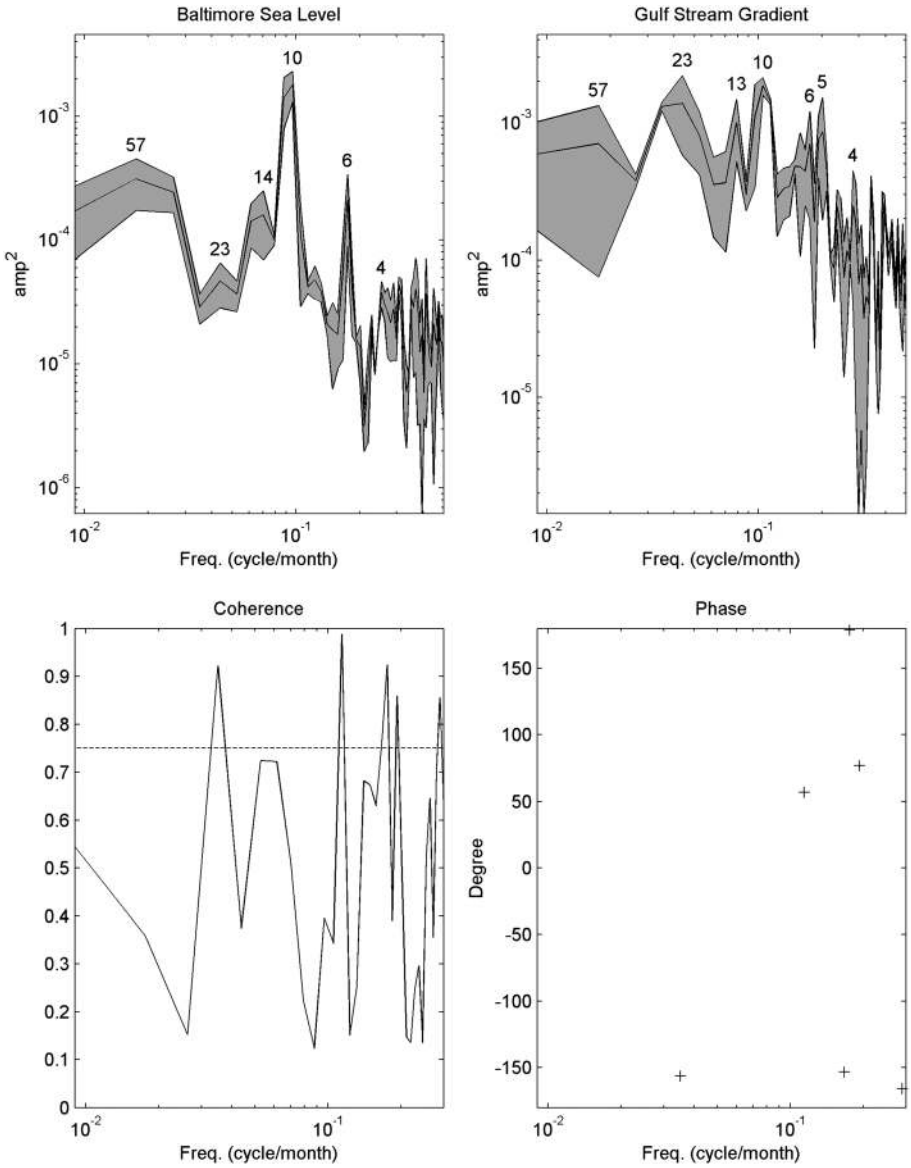

Figure 8. Same as Figure 7 but for power spectra of the sea level in Baltimore and the Gulf Stream gradient (both in m^2).

while the observed GS transport upstream at the Florida Strait represents the sum of the surface-to-bottom flow; thus, it is important to see how the two properties are related to each other. Figure 9 compares the Florida Current transport at 27°N with the average GS gradient along the Mid-Atlantic Bight (35°N–39°N, 70°W–75.5°W). The monthly data of the two time series are only moderately correlated (correlation coefficient of $R = 0.13$ with 95% confidence level), representing seasonal and interannual variations of ~3–5 Sv as described by *Baringer and Larsen* [2001]. In the early observations before 1998, the two time series do not agree as well as in the period after 2000, when large changes within a few months are coherent. For example, for a few months in late 2008 to 2009, the Florida Current transport increased by ~10 Sv from 27 to 37 Sv, while the average GS gradient doubled from 0.8 to 1.6 m/100 km, before weakening again in late 2009. The latter changes may coincide with the findings of *Sweet et al.* [2009], who reported on unusual high coastal sea level in 2009 when the GS transport was relatively low. The long-term variations of the two time series are obtained by combining the last three modes (two oscillating modes plus the trend) of the HHT analysis. The reason for choosing these modes is that they generally represent interannual and decadal variations on timescales longer than those resolved by the spectral analysis (> ~5 years). These low-frequency oscillations of the GS gradient and the Florida Current are highly correlated with each other (correlation coefficient of $R = 0.72$ with 99.99% confidence level). The Florida Current shows oscillations with a period of ~6 years, and the GS shows oscillations with a period of ~8 years, but both indicate a weakening of the current starting around 2002 or 2004.

[14] In Figure 10, the low-frequency HHT modes are used to look at the sea level records (seven from the CB and three from the Atlantic coast). Despite the large geographical distance between the stations (over 300 km and different coastal environments), all records (color lines) show

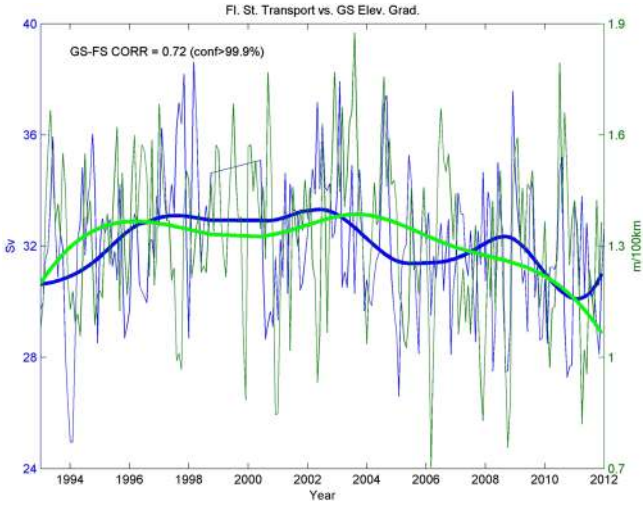

Figure 9. The Florida Current transport across the Florida Strait at 27°N (blue lines; *y* axis in Sv on the left) and the average Gulf Stream Gradient 70°W–75.5°W (green lines; *y* axis in m/100 km on the right). Thin lines are the monthly data, and heavy lines are the combined last three EMD/HHT modes. Note that there is a gap in the Florida Current data between 1999 and 2001. The correlation coefficient between the Florida Current and the GS gradient is $R = 0.13$ (95% confidence significance) for the monthly data and $R = 0.72$ (99.9% confidence significance) for the low-frequency modes.

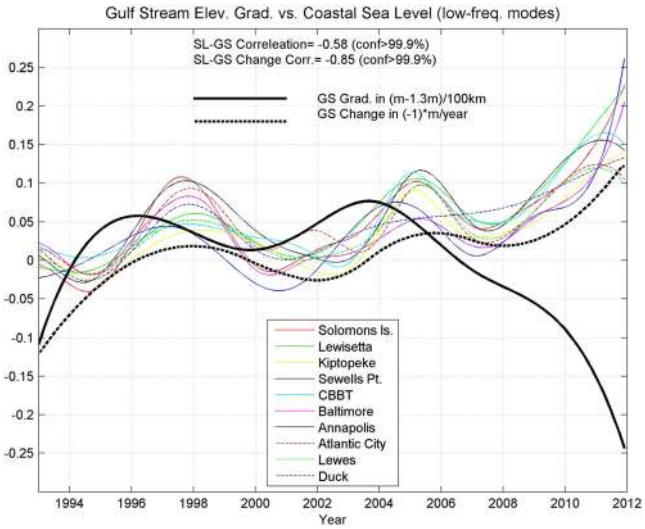

Figure 10. The three HHT modes with the lowest frequency (including the trend) obtained from sea level data at seven CB locations (color solid lines) and three Atlantic coast locations (color dash lines) and from the Gulf Stream gradient data (solid heavy black line). The sea level unit is in meter relative to the average in 1993, and the Gulf Stream gradient anomaly unit is in meter elevation change per 100 km relative to 1.3 m/100 km. Also shown in a heavy black dash line is the time change of the Gulf Stream gradient; the latter has a unit of –m/year/100 km. The negative sign is chosen to better show the similarity between variations of the sea level and the changes in the Gulf Stream, i.e., at the end of the record in December 2011, the Gulf Stream gradient is decreasing by 0.125 m/year.

surprisingly very similar pattern that includes a 6–8 year cycle and a continuous sea level rise in recent years. The 6–8 year cycle includes high anomaly of the sea level in 1997–1998, 2004–2005, and after 2010. The GS gradient (black heavy line in Figure 10) shows two peaks in 1995–1996 and 2003, each about 2 years before the sea level peak, but then a continuous decline in GS strength from 2003 to 2012, when sea level has been significantly rising. The GS gradient is anticorrelated with sea level (average correlation $R = -0.58$ with confidence level greater than 99.99%); a higher correlation is achieved with a lag of 2 years. Note that the tide gauge stations on the Atlantic coast outside the CB show similar pattern to the CB stations. The sea level in Duck, NC (dash blue line), is slightly different from the others in that it does not have the second peak in 1994–1995, but instead, it shows a continuous increase in sea level from 2001 until today. The location of Duck close to the GS separation point from Cape Hatteras may indicate a more direct influence by the GS than other stations do. We also calculate the *change* in the GS strength (the dash heavy line in Figure 10 is the reverse of the GS change, positive values indicate weakening GS) and found that it is even more significantly anticorrelated with the coastal sea level than the gradient itself (average correlation $R = -0.85$ with confidence level greater than 99.99%). The GS gradient shows strengthening at the beginning of the record in 1993 by ~0.125 m yr^{-1}, and by the end of 2011, it was weakening by ~0.125 m yr^{-1} (for every 100 km horizontal distance across the GS). Since the average GS gradient is about 1.3 m/100 km, it implies that long-term trends can increase or decrease the GS strength by as much as ~10% each year, and the recent weakening of the GS is significant. Our results are supported by observational evidence that the volume transport of the AMOC may have decreased between 2004 and 2010 by as much as 30% [*McCarthy et al.*, 2012]. Therefore, the results suggest that a significant driver of the long-term coastal SLR in the mid-Atlantic region is the weakening of the GS. The change in the GS strength shown in Figure 10 may explain the changes in the GS path shown in Figs. 1 and 2. Before 2004, the GS was more energetic and closer to shore, while in the past decade or so, the results indicate weakening of the GS and a more southern path. A more inertial GS may "overshoot" the separation point before bending eastward, while a weaker GS may allow the development of stronger recirculation gyre north of the GS, which "pushes" the GS southward, as shown in numerical ocean circulation models [*Ezer and Mellor*, 1992].

[15] To evaluate the SLR acceleration in recent years, we wanted to look at the SLR rates of the last decade (2002–2011). Calculating SLR rates of a short period of 10 years would not be very reliable by least squares linear curve fitting methods (at least a 60 year record is usually needed), but the HHT method overcomes this problem, because the HHT trend is obtained from the entire record. The time-dependent HHT trend at monthly intervals can be used to calculate averages for a subset of the record. Thus, the average SLR rate of the last decade is simply the average slope of the trend for the period 2002–2011.

[16] Figure 11 summarizes the relation between the SLR rates over the period 2002–2011 (the *y* axis) versus the absolute value of the correlation coefficient between the sea level and the GS gradient (*x* axis). The signs of the correlation

coefficients are all negative, and they are all significant at $>99\%$ confidence (i.e., the statistical confidence that the correlation is not zero). All stations show considerably larger SLR rates during the last decade than the average SLR over the entire observed period, which indicates that SLR is in fact accelerating [*Boon*, 2012; *Ezer and Corlett*, 2012a; *Sallenger et al.*, 2012]. For example, at Sewells Point, near the flood-prone city of Norfolk, VA, the SLR of the entire record is 4.4 mm yr^{-1}, but the SLR of the last decade is around 6 mm yr^{-1}. There are however significant spatial differences in SLR rates between stations. In the CB (blue circles), long-term variations in sea level are all driven by the same Gulf Stream–induced variations at the mouth of the bay (Figure 10), but the large spatial differences in land subsidence at each station [*Boon et al.*, 2010] dominate the SLR rates in the CB. Note, however, that the largest correlation between the GS and the sea level is found at CBBT, which is located near the mouth of the CB, i.e., closer to the direct influence of the GS than the other CB stations inside the bay. In contrast with the wide range of SLR rates in the CB, the three Atlantic stations show more consequential results. SLR rates along the Atlantic coast increase when correlations with the GS increase from north (Atlantic City, NJ) to south (Duck, NC). Therefore, a station that is closer/farther from the GS has a larger/smaller correlation with the GS and a larger/smaller recent SLR rate. It is premature to make quantitative judgment about this direct relation based on only three Atlantic Stations, but qualitatively, the results agree with our hypothesis of the influence of the GS on coastal sea level. In the future, we plan to analyze many more stations.

3.3. A Simple Dynamic Balance of the Gulf Stream Impact On Sea Level

[17] The data show statistically significant correlations between changes in the GS elevation gradient and coastal sea level variations, and Figure 2 qualitatively shows an example that demonstrates that our proposed mechanism of the GS-SLR relation may actually be at work. So what is the dynamic mechanism that allows small changes in elevation gradients hundreds of kilometers offshore to influence coastal sea level? Let us look at a simple dynamic balance under the following assumptions: an offshore elevation gradient ($\partial\eta/\partial x$) is perpendicular to a straight coastline oriented in the north–south (y) direction, the flow is northward (v component) and barotropic over a constant depth H and in a geostrophic balance, all the nonlinear effects are neglected, and there are no alongshore variations ($\partial/\partial y = 0$). Under these simple conditions, the momentum equations are

$$fv = g\frac{\partial\eta}{\partial x} \tag{1}$$

$$\frac{\partial v}{\partial t} = -fu \tag{2}$$

where g and f are the gravitational constant and the Coriolis parameter, respectively. Taking the time derivative ($\partial/\partial t$) of (1), substituting the results into (2) and multiplying by H gives us the following relation:

$$T = uH = -\frac{gH}{f^2}\frac{\partial}{\partial t}\left(\frac{\partial\eta}{\partial x}\right) = -R_d^2\frac{\partial}{\partial t}\left(\frac{\partial\eta}{\partial x}\right) \tag{3}$$

where T is the onshore/offshore transport and $R_d = (\sqrt{gH}/f)$ is the barotropic Rossby radius of deformation (R_d is ~500 km for a continental shelf depth of $H = 250$ m located in midlatitudes). Therefore, from (3), we see that changes in the offshore gradients of elevation (e.g., the GS or the slope current in Figure 2) within hundreds of kilometers from shore can affect onshore/offshore transports and, thus, the coastal sea level. From (1), we also see that if the elevation gradient across the GS is smaller, the northward geostrophic current is weaker, which may allow a stronger southward Slope Current that can raise the coastal sea level. Therefore, both the gradient of elevation itself and changes in the gradient over time may influence the coastal sea level, as shown in Figure 10. It is acknowledged, however, that realistic dynamics are likely to be much more complicated than the simple mechanism suggested in (3) and may involve GS eddies, recirculation gyres in the mid-Atlantic Bight, coastal currents, topographically trapped waves, etc. Nevertheless, (3) suggests an explanation why the coastal sea level has a high correlation with time variations in GS gradients (Figure 10).

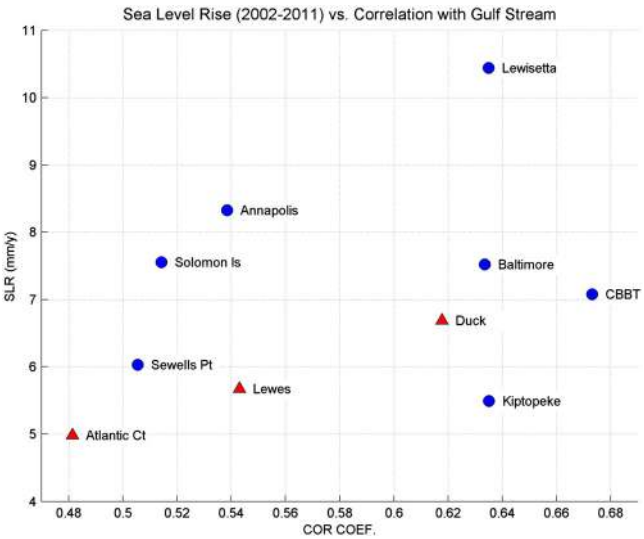

Figure 11. Sea level rise rates over the last decade (2002–2011), obtained from the trend of the HHT analysis, versus the correlation coefficient between the sea level and the Gulf Stream gradient. The correlations are all negative, so only the absolute value is plotted in the x axis. Chesapeake Bay locations are blue circles, and Atlantic stations are red triangles.

4. Summary and Conclusion

[18] This study was motivated by recent findings showing an accelerated SLR ("hot spot") along a stretch of the North Atlantic coast from Cape Hatteras to Cape Cod and possibly even north to Canadian coasts [*Boon*, 2012; *Ezer and Corlett*, 2012a, 2012b; *Sallenger et al.*, 2012]. A potential driver for this SLR acceleration is a climate-related slowdown of the AMOC [*McCarthy et al.*, 2012] and its northward flank, the Gulf Stream (GS). The hypothesis is that a reduction in the GS transport would result in slower surface geostrophic currents, smaller sea level gradients across the GS, and, thus, a higher coastal sea level north of the GS (and, possibly, a lower sea level south of the GS, in the subtropical gyre).

Models and observations support this hypothesis. For example, strong correlations between the transport of the GS and the coastal sea level were previously found in an Atlantic Ocean model simulations of 1950–1990 [*Ezer*, 2001a], in which the decadal variations in this model were about ±5 cm in sea level and about ±5 Sv in GS transport. Here, we found similar or even slightly larger decadal variations in sea level observations from 1993 to 2011 that seem to correspond to decadal variations and climatic changes in the GS. The GS gradient variations in the mid-Atlantic were found to be driven by the Florida Current transport upstream and by the NAO; the latter represents large-scale wind-stress variations that drive slow-moving Rossby waves across the Atlantic Ocean [*Meinen et al.*, 2010]. Establishing the connection between large-scale Atlantic changes and GS gradients may allow us to infer the impact of climatic variability and change on coastal sea level.

[19] There are three findings that we find quite striking: First, the high similarity in the variations of monthly sea level data over large distances and different geographical locations indicates a common large-scale forcing. Local land subsidence, local wind pattern, and local ocean dynamics (e.g., shallow estuarine dynamics in the CB versus Atlantic coastal currents) may play a lesser role in variations over timescales longer than a few months. Second, the very high correlation found ($R = -0.85$) between long-term variations in sea level records and changes in the GS strength imply potential predictive skill for projection of future SLR. Finally, the SLR acceleration in the mid-Atlantic region [*Boon*, 2012; *Ezer and Corlett*, 2012a, 2012b; *Sallenger et al.*, 2012] appears to be associated with a significant weakening of the GS over the past decade or so. This trend shown here for the GS gradient and the Florida Current transport may be supported by recent observations of the AMOC [*McCarthy et al.*, 2012; *Srokosz et al.*, 2012].

[20] Our results may have several practical implications. For example, the results can explain why in recent years an unusually high coastal sea level (sometimes around 30–50 cm above NOAA's storm surge and tidal prediction; http://www.nws.noaa.gov/mdl/etsurge/) can persist for months; these anomalies often cause floods during high tides in places such as Norfolk, VA, even during times when there are no apparent storm surges or other weather events to explain those anomalies. Anecdotal evidences that these anomalies are the result of GS variations have been suggested before [*Sweet et al.*, 2009], but our study shows, in fact, that the likely drivers for those anomalies are variations in the GS. The impact of the GS on coastal sea level is probably a more prominent feature than previously thought and can affect variations on timescales ranging from a few months to decades. The conclusion of our study is that ocean dynamics may play a key role in coastal sea level changes; this conclusion is especially important for regions such as the mid-Atlantic Bight that are influenced by energetic currents such as the GS. Better understanding of past and future variations in the GS perhaps can improve future projections of SLR for flood-prone regions such as the Hampton Roads area in the Chesapeake Bay, which are already battling increasing floods due to sea level rise.

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