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Sea Level Rise, Spatially Uneven and Temporally Unsteady: Why the U.S. East Coast, the Global Tide Gauge Record, and the Global Altimeter Data Show Different Trends

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Sea level rise, spatially uneven and temporally unsteady: Why the U.S. East Coast, the global tide gauge record, and the global altimeter data show different trends

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[1] Impacts of ocean dynamics on spatial and temporal variations in sea level rise (SLR) along the U.S. East Coast are characterized by empirical mode decomposition analysis and compared with global SLR. The findings show a striking latitudinal SLR pattern. Sea level acceleration consistent with a weakening Gulf Stream is maximum just north of Cape Hatteras and decreasing northward, while SLR driven by multidecadal variations, possibly from climatic variations in subpolar regions, is maximum in the north and decreasing southward. The combined impact of sea level acceleration and multidecadal variations explains why the global mean SLR obtained from ~20 years of altimeter data is about twice the century-long global SLR obtained from tide gauge data. The sea level difference between Bermuda and the U.S. coast is highly correlated with the transport of the Atlantic Overturning Circulation, a result with implications for detecting past and future climatic changes using tide gauge data. **Citation:** Ezer, T. (2013), Sea level rise, spatially uneven and temporally unsteady: Why the U.S. East Coast, the global tide gauge record, and the global altimeter data show different trends, *Geophys. Res. Lett.*, *40*, 5439–5444, doi:10.1002/2013GL057952.

1. Introduction

[2] The mid-Atlantic region along the East Coast of the United States has been identified as a "hot spot" of accelerated sea level rise (SLR) since sea level acceleration (i.e., an increase with time of SLR rate) there is much larger than global acceleration [*Boon*, 2012; *Ezer and Corlett*, 2012; *Sallenger et al*., 2012; *Kopp*, 2013]. As a result of this fast regional SLR, low-lying coastal communities in the mid-Atlantic region have seen a significant increase in the frequency of flooding in recent years [*Atkinson et al*., 2013]. In addition to large land subsidence around the Chesapeake Bay area [*Boon et al*., 2010; *Kopp*, 2013], SLR acceleration in the mid-Atlantic has been found to be highly correlated with recent offshore shift and weakening in the Gulf Stream (GS) just north of Cape Hatteras (CH) as seen in altimeter data [*Ezer et al*., 2013, hereinafter E13] (see also Figure S5 in the supporting information). The latter finding is consistent with dynamic sea level changes seen in ocean models [*Ezer*, 1999, 2001; *Levermann et al*., 2005; *Yin et al*., 2009] and expected weakening in the Atlantic Meridional Overturning Circulation (AMOC) under warmer climate conditions [*Hakkinen and Rhines*, 2004; *Sallenger et al*., 2012; *McCarthy et al*., 2012; *Srokosz et al*., 2012]. Though there have been some signs of weakening AMOC since 2004 and weakening GS in the mid-Atlantic since 2004 (E13), the long-term downward trend in the strength of the GS may not be statistically significant so far [*Rossby et al*., 2005, also personal communication, 2013].

[3] The existence of SLR acceleration in the global ocean is even more difficult to assess than the regional acceleration, so published results do not always agree with each other [*Church and White*, 2011; *Houston and Dean*, 2011; *Baart et al*., 2012; *Dean and Houston*, 2013]. One of the hotly debated issues addressed here is the discrepancy between the mean global SLR obtained from ~130 years of global tide gauge data (~1.5 mm yr^{-1}) and that obtained from ~20 years of altimeter data (~3.2 mm yr^{-1}). Is this discrepancy an indication of global SLR acceleration, difference in coverage, instrumental errors, or unresolved long-term cycles? (e.g., the 60 year cycle) [*Chambers et al*., 2012]. Comparisons between tide gauges and altimeter data are often inconclusive about the exact reason for this discrepancy [*Dean and Houston*, 2013]. To address the above problems, the empirical mode decomposition/Hilbert-Huang transformation (EMD/HHT) method [*Huang et al*., 1998; *Wu and Huang*, 2009] was used, following the methodology of *Ezer and Corlett* [2012]. Nonparametric methods such as the EMD and the Gaussian Process (GP) decomposition [*Kopp*, 2013] may have some advantages over standard least squares fitting methods commonly used in sea level studies (see the supporting information).

[4] This study has two main goals: (1) to extend the EMD sea level analysis, previously applied only to the Chesapeake Bay [*Ezer and Corlett*, 2012] and the Mid-Atlantic Bight (E13), to most of the East Coast of the United States, so that connections between spatial patterns in SLR and ocean dynamics can be established; and (2) to study how decadal and multidecadal variations affect SLR and explain the discrepancy between global SLR of tide gauge data and altimeter data.

2. Data and Analysis Methods

[5] Monthly mean sea level records from 11 tide gauge stations with over 60 years of high-quality data (see Table S1) were obtained from the Permanent Service for Mean Sea Level (www.psmsl.org) [*Woodworth and Player*, 2003]. The data include 10 stations along the U.S.

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Figure 1. Map of the study area indicating the location of the 11 tide gauge stations used and the location of the cable across the Florida Strait which measures the transport of the Florida Current (red line). Schematics of the Florida Current and the Gulf Stream mean flow are shown.

East Coast, from Boston, MA, to Key West, FL, and one station offshore, in the North Atlantic Ocean at Bermuda (Figure 1). Altimeter and tide gauge global sea level data are obtained from the Commonwealth Scientific and Industrial Research Organization (www.cmar.csiro.au/sealevel/) [*Church and White*, 2011]. Florida Current (FC) transport data are from cable measurements across the Florida Strait at 27°N (NOAA/AOML; www.aoml.noaa.gov/phod/floridacurrent/); the data include the periods 1982–1998 and 2000–2012. Semidaily AMOC transport at 26.5°N for 2004–2012 was obtained from the RAPID project (www.rapid.ac.uk/rapidmoc) [*McCarthy et al*., 2012].

[6] The analysis method of all time series is based on the EMD (see supporting information), whereas each record is decomposed into a finite number of intrinsic oscillatory modes and a residual "trend" $r(t)$. The frequency in each mode is time dependent, but here modes are grouped in a way that each time series is represented by $\boldsymbol{\eta}(t) = \mathrm{HF}(t) + \mathrm{DO}(t) + \mathrm{MD}(t) + r(t)$, where HF is the sum of the high-frequency modes with average periods $T < 5$ years, DO is the sum of decadal oscillation modes with periods 5 years $< T <$ 15 years, and MD is the sum of multidecadal variations with periods $T > 15$ years. A *multidecadal trend* is defined as $\mathrm{MD}(t) + r(t)$. Land movement (mostly postglacial rebound) is not directly addressed by the EMD but is assumed to have a linear trend, so comparisons between local and global linear SLR trends will tell us about land movement. On the other hand, nonlinear EMD-derived acceleration, $r(t)$, will indicate processes other than land motion (likely ocean dynamics). Figures S1 and S2 show examples of the EMD analysis for the records of sea level in New York and in the global mean sea level, respectively; both records show a positive SLR acceleration. Mode 7, for example, resembles the 60 year cycle discussed by *Chambers et al*. [2012], showing that the local and global sea level records are in phase since ~1920. The low-frequency modes in New York (modes 5–9 in Figure S1) show upward recent trends, which suggest multiple contributions to the recent SLR acceleration. Experiments with ensemble EMD calculations [*Wu and Huang*, 2009] demonstrate that the trends are very robust and insensitive to even high levels of white noise (Figure S3).

3. Results

3.1. Spatial Variations in SLR Trends and Sea Level Acceleration

[7] The linear trends in SLR are shown in Figure 2a, and the mean rates are shown in Figure 3a and listed in Table S1. The large SLR rates in the mid-Atlantic, from Atlantic City to Norfolk, are due to large land subsidence around the Chesapeake Bay [*Boon et al*., 2010; *Kopp*, 2013]; the lowest SLR rate at Wilmington (2.01 mm yr^{-1}) and the highest SLR rate at Norfolk (4.66 mm yr^{-1}) are from close geographical locations but represent different geological settings (the postglacial rebound and the Chesapeake Impact Crater increase land subsidence, especially in the lower Chesapeake Bay [*Boon et al*., 2010]). The SLR trends obtained from the EMD analysis (Figure 2b) are clearly nonlinear and show almost universal positive SLR acceleration (Figure 3b). The spatial pattern of acceleration is much more striking than linear trends (Figure 3a) and is likely the result of ocean dynamics, since long-term geological processes are quite linear and thus were eliminated in Figure 3b. The statistically significant positive acceleration north of Cape Hatteras (CH) is

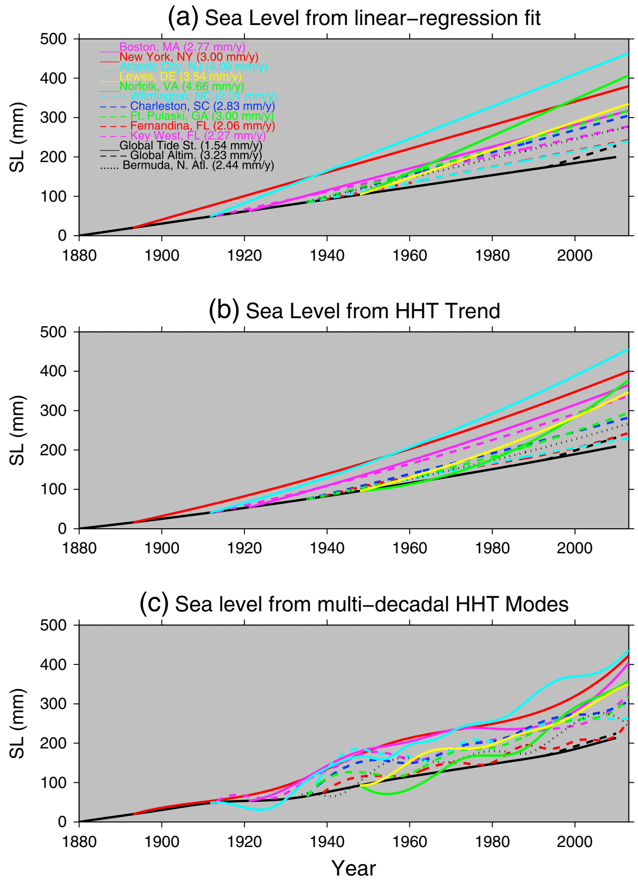

Figure 2. Comparisons between the global sea level obtained from tide gauges (black solid line starting in 1880), from altimeter data (dashed black line starting in 1993), and from local sea level data. Solid/dashed color lines are for coastal tide gauges located north/south of Cape Hatteras on the U.S. coast, and the dotted black line is from Bermuda in the Atlantic Ocean (see Figure 1). Each local record is shifted to match the global mean sea level at the beginning of the record. (a) Linear regression fit lines (the mean sea level rise of each record is indicated). (b) Nonlinear long-term trend obtained from the residual of the EMD analysis. (c) Multidecadal trend of the EMD analysis.

in agreement with the SLR acceleration calculated by quadratic least squares methods [*Boon*, 2012; *Sallenger et al.*, 2012] or GP decomposition [*Kopp*, 2013]. However, the above previous studies show significant SLR acceleration mostly after 1970, while the EMD method removes multidecadal variations from the trend and calculates mean acceleration [i.e., the average of the second derivative of $r(t)$; see equations (S4a) and (S4b)] over entire records. Thus, the EMD calculations give more credibility to the assessment that the "hot spot of accelerated SLR" is real. The global tide gauge data show small positive acceleration, but the global altimeter data show negative acceleration, though the altimeter record length, ~20 years, is too short to make any conclusions from this result. Based on the bootstrap ensemble simulations of *Ezer and Corlett* [2012], the 95% confidence interval around the mean acceleration calculated by the EMD is estimated to be about ±0.01 mm yr^{-2} (see supporting information for details). Therefore, statistically significant positive SLR acceleration is found in Boston, New York, Atlantic City, Lewes, Norfolk, Pulaski, and Bermuda. The spatial pattern of the acceleration in Figure 3b is quite striking, showing a decrease in the impact of the GS as one moves north from CH along the coast, extending the SLR-GS correlation pattern found by E13. Figures 3a and 3b also show the impact of record length on the analysis by comparing the results of the full records with results obtained from the past 60 years ("diamond" markers; see also Figure S4). While the impact of record length on mean linear SLR is relatively small, it is affecting sea level acceleration more profoundly, indicating that SLR rates are in fact changing over time. In particular, the distinction between large positive acceleration north of CH and insignificantly small acceleration south of CH is enhanced over the past 60 years, providing further confirmation to the hot spot of accelerated SLR findings of *Sallenger et al.* [2012]. The significant increase in acceleration over the past 60 years in Boston and New York reflects the impact of multidecadal variations, as discussed in the next section.

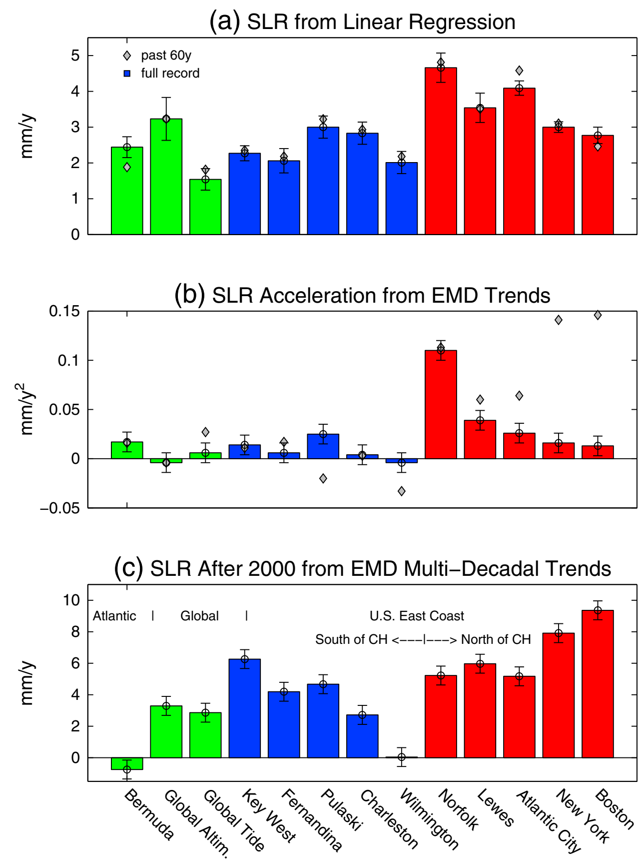

Figure 3. (a) SLR rates obtained from linear regression (see Figure 2a). (b) Average SLR acceleration obtained from the trend of the EMD (see Figure 2b). (c) Sea level rise rates after 2000 obtained from the multidecadal trend of the EMD (see Figure 2c). Red/blue bars are for locations north/south of Cape Hatteras, and green bars are for the global data and the Atlantic Ocean data (Bermuda). The diamond markers in Figures 3a and 3b are for calculations over the past 60 years (all records with about the same length except the shorter altimeter record that remains unchanged; see also Figure S4). The supporting information explains the estimated error bars (95% confidence intervals).

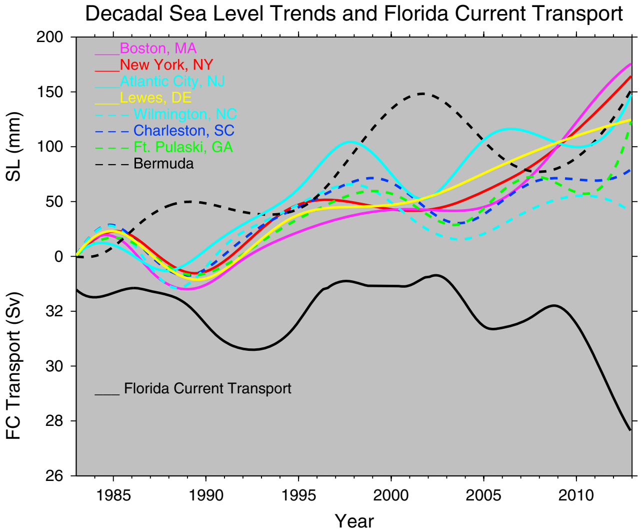

Figure 4. Decadal to multidecadal variations in sea level (top lines) and the Florida Current transport (black solid line on the bottom). Note that the sea level variations on the U.S. coast (color lines) are often in opposite phase to that in Bermuda (dashed black line).

3.2. Multidecadal Variations and Global SLR From Tide Gauges and Altimeter Data

[8] Both the linear trend (Figure 3a) and the acceleration (Figure 3b) show large discrepancy between the global SLR rates obtained from tide gauges and those obtained from altimeter data (even an opposite sign of acceleration). To examine if multidecadal variations are responsible for this discrepancy, the multidecadal sea level trend $\mathrm{MD}(t) + r(t)$ is shown in Figure 2c, and the mean SLR rate after 2000 is shown in Figure 3c. The multidecadal trends show time-dependent SLR rates, thus complicating any calculations based on linear regression. The most interesting result in Figure 3c is that now, the recent SLR rate of the global ocean calculated from tide gauge data (2.86 ± 0.6 mm yr^{-1}) is almost the same as that calculated from altimeter data (3.29 ± 0.6 mm yr^{-1}), i.e., only 15% difference between the two measurements compared with 110% difference in the long-term linear trends (1.54 versus 3.23 mm yr^{-1}, respectively). The results suggest that recent high SLR rates in the global ocean are likely due to the combination of long-term acceleration, $r(t)$, and multidecadal variations, $\mathrm{MD}(t)$. The spatial pattern of recent coastal SLR shown in Figure 3c is in sharp contrast with the SLR acceleration pattern in Figure 3b. The highest MD influence on SLR is in New York and Boston and reducing influence toward CH, suggesting that the source of the multidecadal variations may be climatic changes in subpolar regions [*Hakkinen and Rhines*, 2004] which impact the Labrador Sea outflow [*Rossby et al.*, 2005]. Some increase in recent SLR due to multidecadal variations is also seen southward from CH, suggesting potential impact from variations in the subtropical gyre. The closeness of the GS to the coast south of CH seems to limit shifts in the GS position and changes in its strength compared with locations north of CH (Figure S5), explaining the small sea level changes there, as shown in Figure 3. The location closest to the GS separation point, Wilmington, shows the smallest value for all three SLR indicators, namely, the mean SLR rate, the sea level acceleration, and the impact of multidecadal variations (Figure 3).

3.3. The Relation Between Sea Level, the Gulf Stream, and the AMOC

[9] Sea level records (for clarity, eight records are shown) are compared with the Florida Current (FC) transport in Figure 4, focusing on time scales of decadal and longer, i.e., the combination of $\mathrm{DO}(t) + \mathrm{MD}(t) + r(t)$ from the EMD analysis. The sea level of all the stations along the U.S. coast shows similar patterns of decadal oscillations with minima around 1989 and 2004 and maxima around 1985 and 1999; sea level in Bermuda seems to be in an opposite phase to the coastal stations until about 2007 with distinct maxima around 1989 and 2002. During periods of large differences in sea level between Bermuda and the U.S. coast, such as 1987–1991 and 1999–2004, the FC transport is large, while in years following a weak FC, such as 1992–1994, 2005–2007, and 2011-2012, there is no significant difference in sea level between Bermuda and the U.S. coast. Therefore, it does seem that the sea level difference between the coastal U.S. and the Atlantic (i.e., Bermuda) can detect variations in the GS, as previously shown in ocean models [*Ezer*, 1999, 2001]. Over the past 5 years of data, the pattern has changed with the GS transport declining and sea level rising (similar to the results of E13 who used a shorter GS record from altimeter data). This recent GS slowdown may relate to climate-related weakening of the AMOC, as suggested by *Yin et al.* [2009], *Sallenger et al.* [2012], and others. Observations of the AMOC transport across 26.5°N are available since 2004 [*McCarthy et al.*, 2012]; this record is relatively short, but does it correlate with sea level data? Figure 5 shows a comparison between the EMD modes of the AMOC and those of the sea level difference between Bermuda and Atlantic City after adding a 2 month lag (sea level lags behind AMOC, though the reason of which needs further research). The monthly records of sea level difference and AMOC are significantly correlated ($R = 0.27$ at 95% confidence level), but much higher correlations are found for some modes, in particular, in mode 4 (~3 year period), with $R = 0.81$, and the long-term trends in the AMOC and the sea level (mode 6) are almost identical ($R > 0.99$), with downward trends after 2008. A combination of the low-frequency EMD modes demonstrates the possibility to infer the AMOC transport from sea level (Figure 5, right bottom). Note the significant decline from 2009 to 2010 of the AMOC and the sea level difference that is captured by mode 4.

4. Summary and Conclusions

[10] The study suggests explanations for recent findings of accelerated SLR (hot spot) along the U.S. East Coast north of CH [*Boon*, 2012; *Ezer and Corlett*, 2012; *Sallenger et al.*, 2012; *Kopp*, 2013] and the impact of climate-related changes in the AMOC [*Hakkinen and Rhines*, 2004; *McCarthy et al.*, 2012; *Srokosz et al.*, 2012] and its upper branch, the GS, on SLR. By expanding the results of E13 from the mid-Atlanic region to most of the U.S. East Coast, the results provided further evidence for the role of ocean dynamics on uneven SLR patterns and the role of multidecadal variations on recent SLR.

[11] Two outstanding questions were addressed: (1) how changes in ocean dynamics affect the spatial pattern of

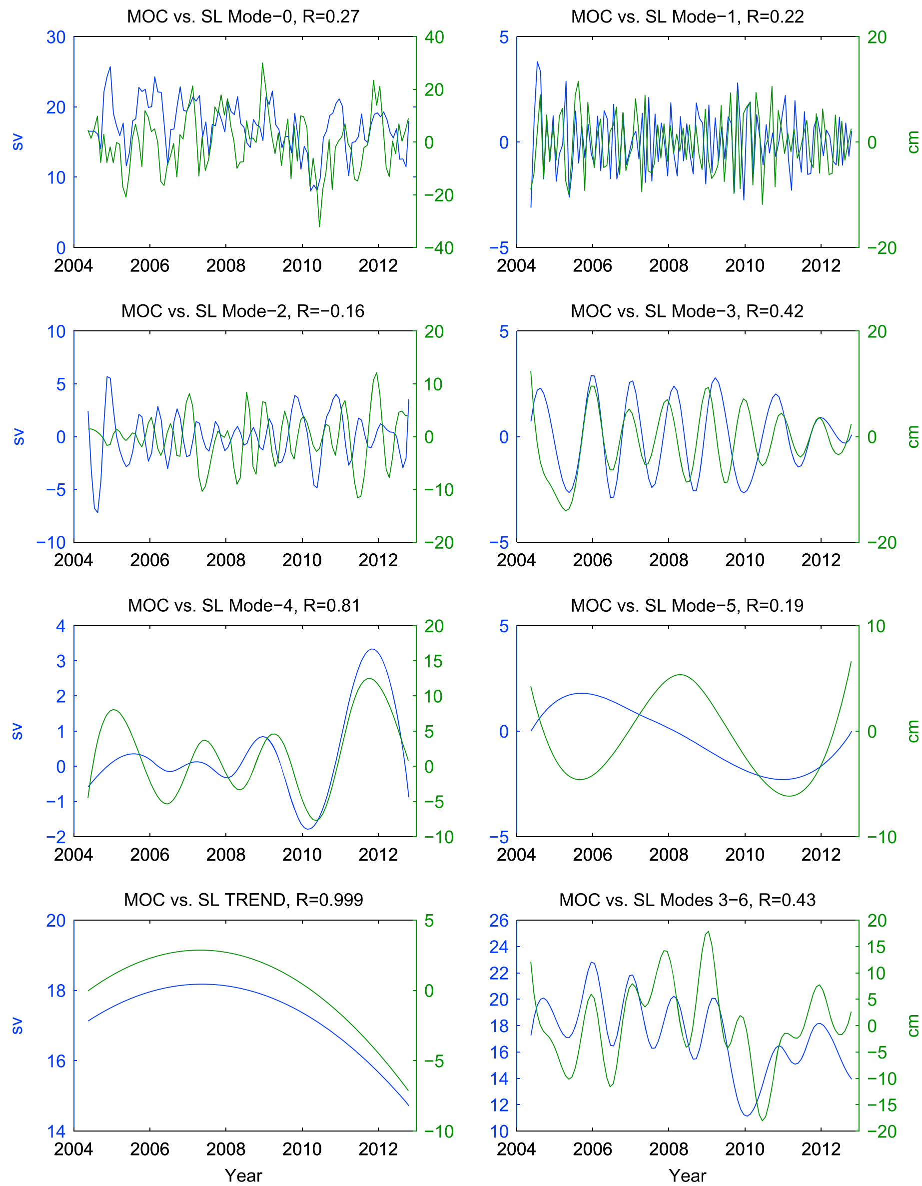

Figure 5. EMD analysis of the Meridional Overturning Circulation (MOC) [*McCarthy et al.*, 2012] time series (blue lines; units in sverdrups on the left) and sea level (SL) difference between Bermuda and Atlantic City (green lines; units in centimeters on the right); *R* is the correlation coefficient between MOC and SL. Mode 0 is the original monthly data, and modes 1–5 are oscillating modes with decreasing frequency. (bottom left) Residual trend (mode 6). (bottom right) Sum of modes 3–6.

SLR along the U.S. East Coast and (2) how decadal and multidecadal variations affect local and global SLR. The EMD analysis shows a clearer spatial pattern of SLR (Figure 3b) than standard least squares curve fitting methods do (Figure 3a), since long-term trends are separated from decadal, multidecadal, and interannual variations. The fact that the long-term SLR acceleration is maximum just north of CH and reduces northward confirms the finding of E13 of maximum GS-SLR correlations in the southern portion of the Mid-Atlantic Bight, where recent slowdown of the GS seemed to increase SLR rates. South of CH, the SLR acceleration is comparable to the (small) global and Atlantic values. A possible reason why the hot spot does not extend southward beyond CH is that south of CH, the GS is flowing closer to the coastline and has smaller variability and cross-stream gradient compared with the GS downstream of the separation point at CH (Figure S5). Another interesting finding is that when multidecadal variations are added to the long-term sea level trend, SLR rates over the last decade or so (Figure 3c) are maximum at high latitudes and decreasing southward toward CH. This result signals that the source of the multidecadal variations in sea level in high latitudes may be coming from climatic variations in subpolar regions [*Hakkinen and Rhines*, 2004]. Decadal and multidecadal variations in sea level are coherent along the U.S. East Coast but are in opposite phase to sea level in Bermuda. Therefore, it was shown here that the difference in sea level between Bermuda and the U.S. coast (i.e., across the GS and its northern recirculation gyre) may be a proxy for changes in the GS and the AMOC. Since sea level is more easily measured and has longer record than AMOC observations, this result may have important implications for studying past and future climatic changes.

[12] The EMD analysis also provides an explanation for the discrepancy in mean SLR (and opposite acceleration

sign) obtained from ~20 years of global altimeter data and ~130 years of global tide gauge data. When multidecadal variations are added to the long-term trend, the recent global SLR rates of the past decade for altimeter and tide gauge data are almost the same. The results suggest that global SLR is accelerating in recent years but that this acceleration is a combination of long-term trends and multidecadal variations.

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