| Journal of Coastal Research | 00 | 0 | 000–000 | Coconut Creek, Florida | Month 0000 |
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# Nonlinear Sea-Level Trends and Long-Term Variability on Western European Coasts

**Tal Ezer[†]*, Ivan D. Haigh[‡], and Philip L. Woodworth[§]**

[†]Center for Coastal Physical Oceanography
Old Dominion University,
Norfolk, VA 23508, U.S.A.

[‡]National Oceanography Centre
University of Southampton,
Southampton, Hampshire SO14 3ZH, U.K.

[§]National Oceanography Centre
Liverpool, Merseyside L3 5DA, U.K.

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**ABSTRACT**

Ezer, T.; Haigh, I.D., and Woodworth, P.L., 0000. Nonlinear sea-level trends and long-term variability on western European coasts. *Journal of Coastal Research,* 00(0), 000–000. Coconut Creek (Florida), ISSN 0749-0208.

Nonlinear trends and long-term variability in sea level measured on the U.K. and western European coasts with long tide-gauge records (~100–200 y) were investigated. Two different analysis methods, a standard quadratic regression and a nonparametric, empirical mode decomposition method, detected similar positive sea-level accelerations during the past ~150 years: 0.014 ± 0.003 and 0.012 ± 0.004 mm/y$^2$, respectively; these values are close to the sea-level acceleration of the global ocean over the same period, as reported by several studies. Ensemble calculations with added white noise are used to evaluate the robustness of low-frequency oscillations and to estimate potential errors. Sensitivity experiments evaluate the impact of data gaps on the ability of the analysis to detect decadal variations and acceleration in sea level. The long-term oscillations have typical periods of 15–60 years and ranges of 50–80 mm; these oscillations appear to be influenced by the North Atlantic Oscillation and by the Atlantic Multidecadal Oscillation. Analysis of altimeter data over the entire North Atlantic Ocean shows that the highest impact of the North Atlantic Oscillation is on sea-level variability in the North Sea and the Norwegian coasts, whereas the Atlantic Multidecadal Oscillation has the largest correlation with sea level in the subpolar gyre and the Labrador Sea, west of the study area.

**ADDITIONAL INDEX WORDS:** *Sea-level oscillations, sea-level acceleration, empirical mode decomposition, North Atlantic oscillations*.

## INTRODUCTION

Nonlinear variations in sea level may include both oscillatory changes, such as decadal and multidecadal variations, as well as changes in the long-term sea-level rise (SLR) rates because of global sea-level acceleration associated with increased rates of land-based ice melt or climatic changes in ocean circulation or wind patterns. In most regions of the world's ocean, there are indications for increasing rates of coastal SLR, but detecting statistically significant long-term sea-level acceleration (on century-long scales) is difficult because of the need to remove decadal and multidecadal variations (Calafat and Chambers, 2013; Dangendorf *et al.*, 2014; Haigh, Nicholls, and Wells, 2009; Haigh, *et al.*, 2014; Wahl *et al.*, 2013; Woodworth *et al.*, 2009a,b). There are also significant spatial variations in both linear and nonlinear trends in the sea level (Boon and Mitchell, 2016; Ezer, 2013). Boon (2012) and Sallenger, Doran, and Howd (2012) indicated temporal changes in acceleration along the U.S. East Coast but with marked larger, positive acceleration in recent years, especially north of Cape Hatteras, where the Gulf Stream (GS) separates from the coast. Nonlinear trends make it difficult to assess whether the recent acceleration is part of natural variations or long-term global trends. Detecting sea-level acceleration is especially difficult because of the need to separate between oscillatory changes and long-term trends. Therefore, various different analysis methods have been used to detect acceleration (see Visser, Dangendorf, and Peterson [2015] for a review of a wide range of such methods). Two different analysis methods are used here to detect sea-level acceleration and demonstrate their usefulness: a standard quadratic regression (fitting the data with the simplest polynomial model of an acceleration curve) and a nonparametric empirical mode decomposition (EMD; Huang *et al.*, 1998); the methods will be described in detail later. An attractive characteristic of the EMD is that it is a more-objective method than parametric regression methods because EMD does not assume a specified formula for the trend and the filtering of oscillations of different timescales is done by an empirical sifting process without specifying a particular filter. As discussed later, there are also some shortcomings in the EMD method. An EMD analysis to help study nonlinear variations and the forcing mechanisms of sea level will be demonstrated, using long records of European sea-level tidal gauges. Because nonlinear variations in sea level are regional, the variations on the western European coasts can be compared with global SLR and variations of sea level in other regions.

Recent studies focus attention on a "hotspot" in the western part of the North Atlantic Ocean, where SLR and sea-level acceleration are significantly greater than global rates (Boon, 2012; Ezer, 2013; Ezer and Corlett, 2012; Kopp, 2013; Sallenger, Doran, and Howd, 2012; Yin and Goddard, 2013). Studies suggest that the SLR pattern on the western side of the

*DOI: 10.2112/JCOASTRES-D-15-00165.1 received 31 August 2015; accepted in revision 16 October 2015; corrected proofs received XX Month XXXX; published pre-print online XX Month XXXX.*
*Corresponding author: tezer@odu.edu

North Atlantic Ocean may relate to the response of coastal sea levels to weakening in the Atlantic meridional overturning circulation (AMOC; Smeed *et al*., 2013; Srokosz and Bryden, 2015; Srokosz *et al*., 2012) and a potential slowdown in the GS flow (Ezer 2013, 2015; Ezer *et al*., 2013; Rahmstorf *et al*., 2015). The impact of ocean dynamics on sea level can also be seen in the mean sea-level tilt along the U.S. East Coast (Higginson *et al*., 2015).

Unlike the western North Atlantic coasts, on the eastern side of the North Atlantic, near the coasts of the U.K. and western mainland Europe, there is no one dominant current like the GS, so it may be more challenging to find a similar, dynamically driven pattern of sea level. The dynamics of sea level and SLR on European coasts are thus more complex and are influenced by local processes, such as coastally trapped waves, local steric effects, and nearshore winds (Dangendorf *et al*., 2014; Haigh, Nicholls, and Wells, 2009; Whal *et al*., 2013; Woodworth *et al*., 1999, 2009a). Longshore winds and wave propagation along boundaries have especially significant impacts on variations in sea level near the eastern margins of ocean basins (Calafat, Chambers, and Tsiplis, 2012; Sturges and Douglas, 2011), such as in the eastern North Atlantic region studied here. Studies have found that large-scale patterns, such as the North Atlantic oscillation (NAO; Hurrel, 1995), correlate with decadal variations in European sea level and thus can result in coherent sea-level variations (Calafat, Chambers, and Tsimplis, 2012; Hughes and Meredith, 2006). The impact of atmospheric pressure on sea level through the inverted barometer (IB) effect can also contribute to interannual and decadal variations, as seen in the western North Atlantic coasts (Piecuch and Ponte, 2015) and in the eastern North Atlantic and the Mediterranean Sea regions (Gomis *et al*., 2008). In any case, modeling the contribution of large-scale, atmospheric and ocean processes to interannual variation in sea level is very challenging and not fully understood yet (Woodworth *et al*., 2009b). The impact of the NAO through wind and atmospheric pressure can be seen, for example, in sea-level variations in the North Sea (Chen *et al*., 2014; Dangendorf *et al*., 2014; Tsimplis *et al*., 2005a; Wakelin *et al*., 2003) and in the Mediterranean Sea (Calafat, Chambers, and Tsiplis, 2012; Tsimplis *et al*., 2005b, 2013). The EMD analysis can be used as a tool to study these variations, as will be demonstrated here.

Two main goals were the focus of this study. First, a study of the long-term (more than a century) sea-level acceleration on U.K. and western European coasts using two different analysis methods. The purpose of this part is to see whether the two methods are consistent with each other and to see whether a coherent acceleration or deceleration pattern emerges in this region. Second, the EMD was used to study low-frequency periodicity in the sea-level data and to try to connect sea-level variations and periodic variations in climate indexes. The two topics are closely related to each other because long-term oscillations result in nonlinear changes in SLR and may appear as acceleration or deceleration trends if record length is not much longer that the period of the oscillations. The ability of statistical analysis to separate between long-term oscillations and long-term trends is crucial, and thus, it is evaluated here with the help of the EMD method.

## METHODS

The complex, nonlinear, sea-level variations on European coasts, as reviewed above, motivated us to employ a method that is different from the more commonly used regression methods; it has some advantages over standard methods and its application to detect acceleration in sea level is relatively new. The EMD (Huang *et al*., 1998) method has been used as a signal processing tools in numerous fields (*e.g.,* medical, seismology, and economical and geophysical data), but, more recently, the method has been adapted for sea-level analysis (Ezer and Corlett, 2012) and used to connect variations in sea level along the U.S. East Coast with changes in the AMOC, the GS (Ezer 2013, 2015; Ezer *et al*., 2013), and the Florida Current (Park and Sweet, 2015). A nonparametric method, such as EMD, is a useful tool for analyzing nonlinear time series and to separate long-term trends from oscillating modes. There is no reason to assume that a sea-level trend is linear or even quadratic; thus, nonparametric methods have more flexibility than traditional methods in describing the shape of the trend. Studies with the EMD analysis (Ezer 2013; Ezer *et al*., 2013) were able to detect low-frequency variability, such as the ~60-year-long cycle (Chambers, Merrifield, and Nerem, 2012) that may relate to the Atlantic multidecadal oscillation (AMO). However, separating this long cycle from the trend requires very long records, thus this study focused on some of the longest records available in the study area (~100–200 y). The accuracy and ability of EMD to detect acceleration is still being evaluated by various ways (Chambers, 2015; Kenigson and Han, 2014), so here EMD-derived sea-level acceleration is compared with results from a standard polynomial fitting method (*e.g.,* Boon and Mitchell, 2016).

Monthly mean sea-level records from tide gauge stations (see Table 1 and Figure 1) were obtained from the Permanent Service for Mean Sea Level (PSMSL, http://www.psmsl.org; Holgate *et al*., 2013; Woodworth and Player, 2003), with additional data provided for Southampton by Haigh, Nicholls, and Wells (2009). Note that the IB effect from atmospheric pressure (Piecuch and Ponte, 2015) was not removed from the data; IB and wind are both part of the atmospheric influence on sea level. Steric effects may also influence sea level and include the seasonal warming–cooling variations and long-term changes in sea surface temperature. Seasonal variations were not explicitly removed from the data, but they were captured by the EMD modes. The main data include eight very long stations, four on U.K. coasts and four on western European coasts with starting dates between 1807 and 1865. Two stations with shorter records (Dublin and Southampton, starting in the 1930s) were also included in Table 1, but they were not part of the full analysis of long-term acceleration. Note that the very long records were originally obtained from different instruments and different organizations, and tide gauges were sometimes relocated over the years with potential shift in datum. In some stations, such as at Aberdeen, data from two records have been combined into one record without any apparent problems (Woodworth *et al*., 1999). Some stations have large gaps in data (Figure 2; Table 1), which makes it a difficult task to study sea-level oscillations. Because the standard EMD code is not built to deal with gaps, experiments show that the best way to analyze those records is to fill the

Table 1. *Sea-level stations and trends. Acceleration and estimated errors are obtained from the EMD (EMD-ACC) and quadratic regression (Quad-ACC); see text for details on how errors were calculated for each method. The accelerations that are statistically significant (i.e. positive and different than zero) are highlighted in bold. Stations with relatively shorter record (*) or with suspected datum shifts (+) are excluded from the mean.*

| Station | Latitude | Longitude | Data Coverage (%) | Period | Mean SLR (mm/y) | EMD-ACC (mm/y$^2$) | Quad-ACC (mm/y$^2$) |
|---|---|---|---|---|---|---|---|
| Aberdeen, U.K. | 57.15°N | 2.08°W | 95 | 1862–2013 | 0.851 ± 0.043 | **0.009** ± 0.003 | **0.009** ± 0.002 |
| North Shields,+ U.K. | 55.01°N | 1.44°W | 94 | 1895–2013 | 1.657 ± 0.022 | −0.005 ± 0.004 | −0.005 ± 0.004 |
| Liverpool, U.K. | 53.45°N | 3.02°W | 70 | 1858–2013 | 1.113 ± 0.015 | **0.020** ± 0.004 | **0.025** ± 0.003 |
| Newlyn, U.K. | 50.103°N | 5.54°W | 98 | 1915–2013 | 1.988 ± 0.037 | **0.010** ± 0.007 | **0.010** ± 0.006 |
| Dublin,* Ireland | 53.35°N | 6.22°W | 99 | 1938–2009 | 2.761 ± 0.310 | **0.100** ± 0.030 | **0.130** ± 0.010 |
| Southampton,* U.K. | 50.88°N | 1.39°W | 100 | 1935–2011 | 2.124 ± 0.200 | **0.065** ± 0.019 | **0.062** ± 0.010 |
| Cuxhaven, Germany | 54.62°N | 8.38°E | 100 | 1843–2010 | 2.450 ± 0.090 | **0.020** ± 0.004 | **0.013** ± 0.003 |
| Den Helder, The Netherlands | 52.97°N | 4.75°E | 100 | 1865–2013 | 1.181 ± 0.007 | 0.002 ± 0.003 | 0.003 ± 0.003 |
| Vlissingen, The Netherlands | 50.67°N | 3.60°E | 100 | 1862–2013 | 1.205 ± 0.080 | **0.017** ± 0.004 | **0.030** ± 0.003 |
| Brest, France | 48.38°N | 4.50°W | 90 | 1807–2012 | 1.034 ± 0.047 | **0.010** ± 0.001 | **0.009** ± 0.001 |
| Mean of longest records | | | 93 | 155 y | 1.403 ± 0.045 | **0.012** ± 0.004 | **0.014** ± 0.003 |

gaps with the value of the linear trend of the entire record (local interpolation for each gap was found to create larger errors in the EMD analysis when compared with data without gaps). The ability of the EMD analysis to overcome some of these difficulties will be evaluated, and in particular, the impact of gaps on the ability of EMD to detect long-term oscillations will be tested.

In the EMD analysis (Huang *et al*., 1998), each sea-level record ($\eta$) is decomposed into a finite number of intrinsic oscillatory modes $c_i$ and a residual "trend" $r(t)$. The number of modes depends on the record length and the variability of the data. Unlike regression-fitting methods, the shape of the trend is not predetermined (*i.e*. the method is "nonparametric"); the trend is obtained by a sifting process that filters out all oscillating modes until a residual remains with no more than one extremum (Wu *et al*., 2007). A periodic oscillation with a period longer than the record itself will appear as a residual trend in any analysis method. Note that each individual mode does not necessarily represent a particular physical process unless a mode or a group of modes are specifically shown to relate to a known forcing, say a seasonal cycle or the NAO index (*e.g.,* Ezer *et al*., 2013). If the EMD identifies $N$ oscillating modes (with a possible error $\varepsilon$), the original time series can be represented by the following equation:

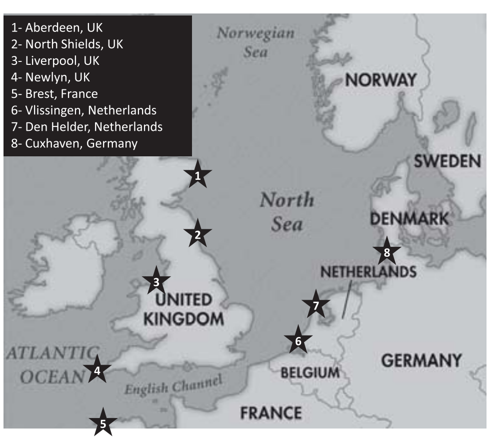


Figure. 1. Map of the study area and location of tide gauge stations (see Table 1 for more details).

$$\eta(t) = \sum_{i=1}^{N} c_i(t) + r(t) + \varepsilon \tag{1}$$

The mean sea-level rise rate (MSLR in mm/y) can be calculated as the time-averaged change in the trend $dr/dt$ and the mean acceleration (ACC in mm/y$^2$) is the time-averaged $d^2r/dt^2$. For example, if there are $M$ monthly records

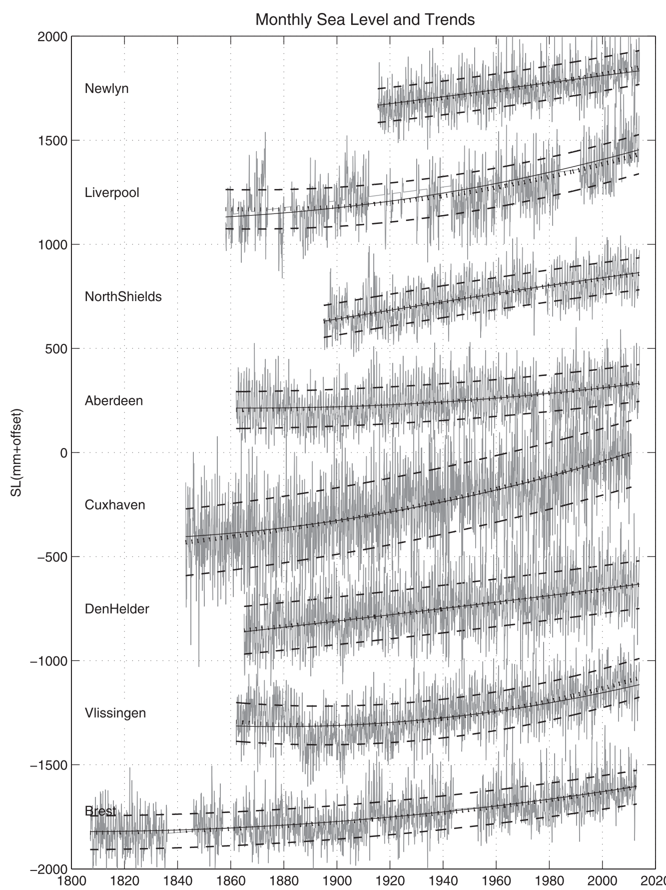


Figure 2. Monthly sea-level data (gray) and the long-term trends (black) obtained from the EEMD calculations (solid line) and from quadratic fit calculations (vertical heavy lines). The standard deviations relative to the quadratic fit are shown by the dashed lines.

($\Delta t$ = 1/12 y), the instantaneous SLR between month $i$ and month $i+1$ is $(r_{i+1}-r_i)/\Delta t$ and the acceleration at that time is $\{[(r_{i+1}-r_i)/\Delta t]-[(r_i-r_{i-1})/\Delta t]\}/\Delta t=(r_{i-1}-2r_i+r_{i+1})/\Delta t^2$. Therefore, the mean SLR over the entire record is

$$MSLR=\frac{1}{\Delta t(M-1)}\sum_{i=1}^{M-1}(r_{i+1}-r_i) \qquad (2)$$

and the mean acceleration is

$$ACC=\frac{1}{\Delta t^2(M-2)}\sum_{i=2}^{M-1}(r_{i-1}-2r_i+r_{i+1}). \qquad (3)$$

A more common way to detect sea-level acceleration is by regression analysis, fitting the monthly data to a quadratic polynomial function (*e.g.,* Boon, 2012):

$$r^q(t)=A+Bt+\frac{1}{2}Ct^2+\varepsilon. \qquad (4)$$

In the quadratic trend $r^q$, the regression coefficient $C$ will represent the mean acceleration because $d^2r^q/dt^2=C$ and can be compared with the $ACC$ of the EMD method, whereas $B$ is the linear trend that can be compared with the $MSLR$ of the EMD. There are advantages and disadvantages to each method, so acceleration derived from Equations (1) and (4) will be compared.

Because linear statistical methods are not valid for calculating confidence levels in EMD (Huang *et al.*, 2003), various approaches have been tried in different studies. For example, Ezer and Corlett (2012) used bootstrap simulations (a special case of Monte Carlo simulations), wherein random samples of anomalies from the data itself are used to form an ensemble (Mudelsee, 2010). Kenigson and Hu (2014) used artificially constructed time series to evaluate the accuracy of detecting known acceleration when multidecadal variations exist. Huang *et al.* (2003) introduced variations in the sifting parameters of the EMD to produce a sample set of EMD modes that can be used to estimate errors. Here, another method is tested using the Ensemble EMD (EEMD; Wu and Huang, 2009). The EEMD was developed to improve the accuracy of the calculations by repeating EMD calculations (as in Equation 1) $N$ times, each time with different white noise (with a chosen standard deviation that is $D$% of the standard deviation of the original data). The means of the ensemble members for each mode ($c_i$ in Equation 1) and residual ($r$) are more accurate than individual EMD calculations because the EEMD filters out unphysical modes and limits the impact of mode shifting (see Wu and Huang, 2009, for details). The EEMD was not originally intended for calculating confidence levels, but it was found that by a careful selection of the EEMD parameters, it can mimic bootstrap calculations and estimate errors based on the spread (standard deviation) of the ensemble, as described below. Later, the error bars in the acceleration estimated by the EEMD will be shown to be surprisingly similar to errors calculated by standard regression statistics, despite the completely different approaches. The number of simulations chosen was $N=100$ and the white noise level chosen was $D=$ 10% of the standard deviation of the data; these values were chosen empirically to provide a spread of the ensemble members that is similar in its statistics to the bootstrap method (Mudelsee, 2010). A comparison (not shown) of the confidence interval obtained from the EEMD calculations and from the bootstrap simulations of Ezer and Corlett (2012) shows very similar results. The estimated errors in Table 1 (95% confidence intervals) were calculated as follows. For the quadratic calculations, a standard regression least-square statistics is used with a $p$ value of 0.05 to estimate the error in the coefficient $C$ in Equation (4). For the EEMD calculations, the error was estimated from the spread of the ensemble members. The EEMD provides $N$ estimates of the trend $r(t)$ in Equation (1) and $N$ estimates of the mean acceleration in Equation (3). Therefore, from the standard deviation around the mean and $N$, the confidence level can be estimated (assuming the $N$ calculations with different white noise are independent estimates and have normal distribution). Although there is no assurance that the statistics of the EEMD follow these assumptions, the final error estimates are comparable to the bootstrap calculations, as described above. Note that hereafter *EMD* and *EEMD* will be used interchangeably, although all the calculations are based on the EEMD code.

Given the large variety of statistical methods used to detect nonlinear sea-level trends and to estimate errors (*e.g.,* Visser, Dangendorf, and Peterson [2015], review 30 different methods), one may argue that there is no agreeable "best" or "correct" method, so each approach has to be taken in its own context with its limitations and, preferably, compared with other methods as done here. The statistical confidence levels for nonlinear methods are not mathematically the same as standard regression methods, but they do provide a tool to evaluate errors and confidence in the results.

## RESULTS

The results first show the nonlinear, long-term trends (acceleration or deceleration) as obtained from the two methods, the EMD and the quadratic regression; then, the robustness of the long-term oscillations and trends are evaluated, and finally, the relation between the long-term oscillations and climatic variations in the Atlantic Ocean is discussed.

### Nonlinear Trends and Acceleration

The monthly sea level at eight locations (Figure 1) is shown in Figure 2, together with the EMD trend of each record (solid black lines) and the quadratic fitting line (dash lines). Standard deviation around the quadratic line is also shown (dash lines). The standard quadratic lines and the EMD-based trends are very close to each other (see also Table 1 for a comparison of the mean acceleration in the two methods), which provides confidence in the results. A slight discrepancy between the trends of the two methods is seen in the record in Liverpool, which had more large gaps than any other records (about 30% of the data were missing in Liverpool; see Table 1). The impact of gaps on both the long-term trend and the low-frequency oscillations will be evaluated later.

Qualitatively, it is immediately clear that the records have very different variability and trends. For example, the easternmost station in the North Sea, Cuxhaven, Germany, has more high-frequency variability than do the other stations, likely because of local, wind-driven coastal dynamics, as

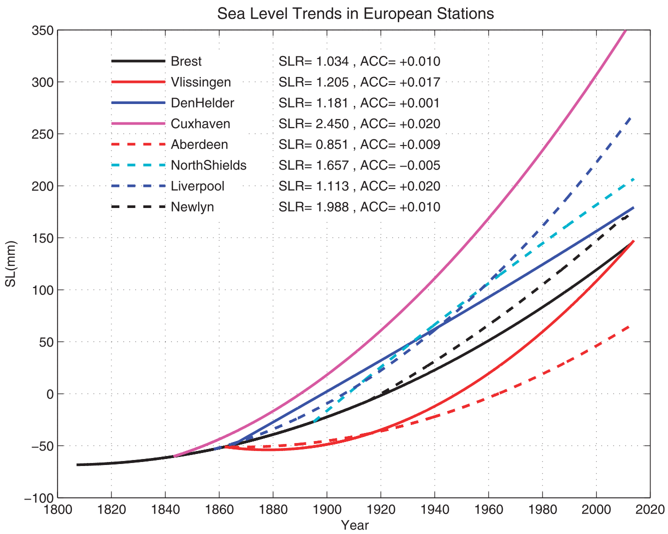


Figure 3. Sea-level trends from the EEMD analysis. The mean linear sea-level rise (SLR in mm/y) and the mean acceleration (ACC in mm/$y^2$) are indicated. For clarity, the records are shifted to start from the same sea level as in the longest record at Brest (black line).

indicated before (Dangendorf *et al.*, 2013, 2014; Wahl *et al.*, 2013); sea level at that station showed a significant correlation with the NAO in the past (Tsimplis *et al.*, 2005b). The calculations show that all the stations, except North Shields, have positive accelerations, and eight of 10 stations in Table 1 have positive acceleration that is statistically significant when using either EEMD or quadratic regression. Figure 3 summarizes the trends of all the stations with long records. The only negative acceleration, at North Shields, may be attributed to observational error—the tide gauge there was relocated in the 1980s after a long gap in the data (Figure 2), and a potential shift in the datum at this station has been suspected, as indicated previously by Woodworth *et al.* (1999). This demonstrates the difficulty in analyzing observations taken over very long periods with different instruments at not precisely the same location. The North Shield record was thus excluded from the mean acceleration of all long stations in Table 1. The relative secular SLR derived from the EMD (*i.e.* the average slope of the trend) for the study area, ~1–2 mm/y, is for most stations very consistent with results from standard regression analysis (Haigh, Nicholls, and Wells, 2009; Wahl *et al.*, 2013; Woodworth *et al.*, 1999, 2009a,b). Note that there is no relation between the mean local SLR, which is largely influenced by local land subsidence (Woodworth *et al.*, 1999), and acceleration, which is influenced by global SLR (Church and White, 2006, 2011) and, possibly, ocean dynamics (Ezer *et al.*, 2013; Leverman *et al.*, 2005; Yin and Goddard, 2013). Similar results with different spatial patterns for linear SLR and acceleration were also found around the U.S. coasts (Boon and Mitchell, 2016). The mean sea-level acceleration found here for the longest records (~150 y) is 0.014 ± 0.003 and 0.012 ± 0.004 mm/$y^2$, for the quadratic and EMD equations, respectively (Table 1). That result is only slightly larger than previous estimates of acceleration in this region, 0.008–0.016 mm/$y^2$ (Woodworth *et al.*, 1999) and is in line with the global acceleration of ~0.01 mm/$y^2$ (Church and White, 2006, 2011). The agreement between the detected acceleration from the EMD calculations and that obtained by standard regression methods confirms the robustness of the EMD method while providing a new method to evaluate the statistical significance of the detected acceleration. The similarity between the confidence intervals obtained by the two completely different methods, one from the ensemble EMD and one from the regression calculation, show that the new approach to estimating errors in the EMD is quite reasonable.

Interestingly, the two "shorter" records for Dublin and Southampton (still more than 70 y long; Table 1) show a larger mean linear SLR and a larger acceleration, 0.06-0.1 mm/$y^2$, than the longer records do; the magnitude of the acceleration in these two stations is similar to the large acceleration in the "hotspot" region of the U.S. East Coast (Boon, 2012; Ezer, 2013; Sallenger, Doran, and Howd, 2012). Trends in shorter records may be influenced more by unresolved AMO variations, such as the ~60 year cycle (Chambers, Merrifield, and Nerem, 2012; Kenigson and Han, 2014), or by recent shifts in ocean currents (Ezer, 2015; Ezer *et al.*, 2013; McCarthy *et al.*, 2012; Srokosz *et al.*, 2012). Therefore, one cannot conclusively say whether the results in Dublin and Southampton are a sign of recent, increased sea-level acceleration or are due to unresolved long cycles. Unlike the western North Atlantic coasts, in which the large sea-level difference across the GS affects the pattern of sea-level acceleration along the coast (see figure 3 in Ezer [2013] or figure 13 in Woodworth *et al.* [2014]), there is no such dominant current in the eastern North Atlantic and thus the pattern of acceleration (Figure 3) does not show a clear distinction between, for example, the U.K. Atlantic coasts and the North Sea coasts.

## Separating Oscillations and Long-Term Trends

Although the EEMD analysis has been applied to all the stations (Table 1), it is constructive to demonstrate how the analysis works; the two stations with the longest records are thus compared. Brest is the southernmost station on the edge between the English Channel and the Atlantic Ocean (Figure 1); it has the longest record, starting in 1807, but it also has several long gaps of several years each (Figure 2; *e.g.,* during and following World War II). Considerable detail on this particularly long record was discussed in Wöppelmann, Pouvreau, and Simon (2006).

Cuxhaven is the easternmost station, located in the North Sea; it has the second longest record (after Brest) and has a continuous record with no significant gaps; details from this station are discussed in Tsimplis *et al.* (2005b) and Dangendorf *et al.* (2013). The EEMD modes are shown for the above two stations in Figures 4 and 5, respectively. Brest, with its longer record, has 10 oscillating modes and Cuxhaven has eight. The gaps in the data affect only the high-frequency EMD modes, so the low-frequency modes do not appear to exhibit any discontinuity. Nevertheless, sensitivity studies, discussed later, will specifically evaluate the effect of gaps in the data. Mode-1 captures the fact that the highest-frequency variability along the SE coast of the North Sea at Cuxhaven is about twice as large (approximately ±200 mm) as that in Brest (approx-

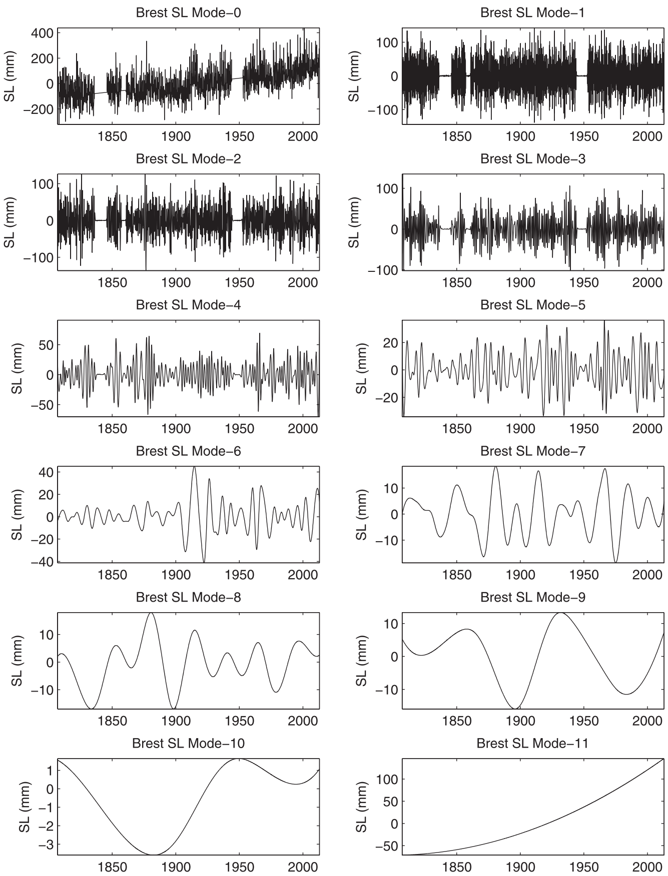


Figure 4. Example of the EEMD analysis for monthly sea level at Brest. Mode 0 is the original record, modes 1–10 are the oscillating modes (from high- to low-frequency), and the last mode (11 in this case) is the residual/long-term trend.

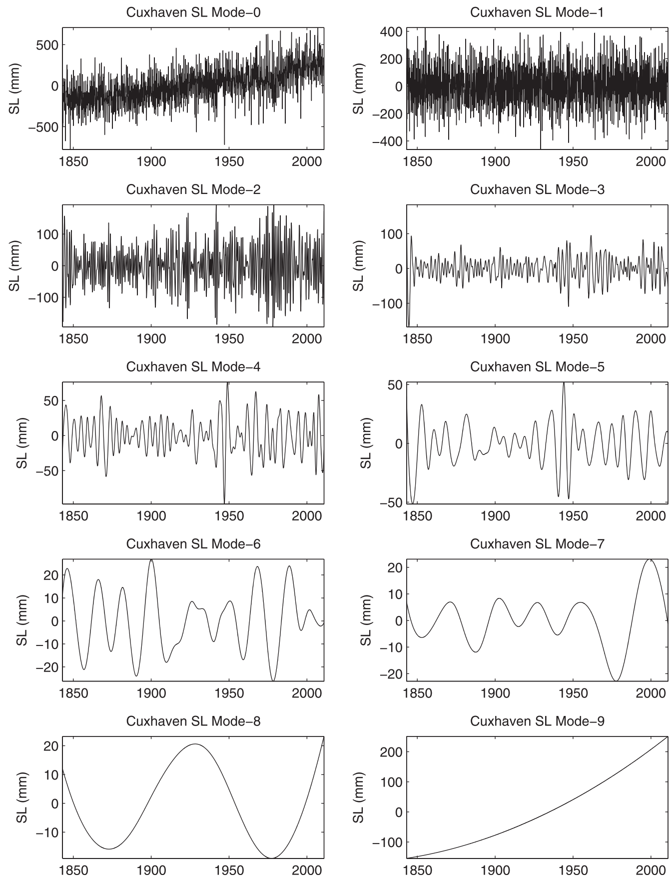


Figure 5. Same as Figure 4, but for sea level at Cuxhaven. The trend in this case is represented by mode 9.

imately ±100 mm). As mentioned before, a single low-frequency mode may not necessarily represent a particular process, but it may hint at forcing mechanisms to look for. For example, the coherency, since 1900, between mode 9 in Brest and mode 8 in Cuxhaven is noticeable, with a maximum around 1930, a minimum around 1980, and an upward trend in recent years. Whether the low-frequency variations are coherent or not across stations and the potential relation to climate indexes will be evaluated later. Both stations show a long-term trend of clear positive acceleration that is distinctively different than a linear trend (*r* in Equation 1 is represented here by mode 11 in Brest and mode 9 in Cuxhaven).

To get a more quantitative look at the significance of the long-term variability and trend, ensemble calculations (EEMD) are employed (Wu and Huang, 2009), as described in the method section. The main purpose here is to test the robustness of the low-frequency variability. The amplitude of the noise may represent potential data errors (*i.e.* for variations of ±100–200 mm in Figures 4 and 5, 10–20 mm error is quite reasonable). Note that sensitivity experiments with different levels of noise from 10% to 100% of the standard deviation reveal relatively little effect on low-frequency oscillations that are real because the ensemble mean will eliminate oscillations that are artifacts of the noise (see supplemental material in Ezer, 2013). Figures 6 and 7 show the results for the two stations discussed before for the combined last three low-frequency oscillating modes and for the trend. Larger errors (the spread of individual simulations shown in thin gray lines) near the start and end of records is quite common in EMD calculations because the sifting process and have indicated in other studies (Ezer and Corlett, 2012; Wu and Huang, 2009).

At Brest, larger multidecadal variations are found during the 19th century and somewhat smaller during the 20th century (Figure 6a). The longest period of oscillations is ~60 years, similar to the AMO-like cycles discussed by Chambers, Merrifield, and Nerem (2012). It is interesting to note two periods with anomalously low sea level in Brest, around 1900 and 1980. However at Cuxhaven (Figure 7a), the first period has maximum peak in sea level (the opposite of Brest), whereas the second period has a minimum (similar to Brest); it will be shown later that this behavior may be related to variations in the NAO and AMO. The trend at Brest obtained by the EMD method (Figure 6b) shows positive acceleration for 1807–2012 of $0.010 \pm 0.001$ mm/y$^2$ for the EMD calculations and $0.009 \pm 0.001$ mm/y$^2$ for the quadratic calculations (Table 1). This acceleration is slightly larger than the acceleration reported by Wöppelmann, Pouvreau, and Simon (2006) for 1807–2004 of

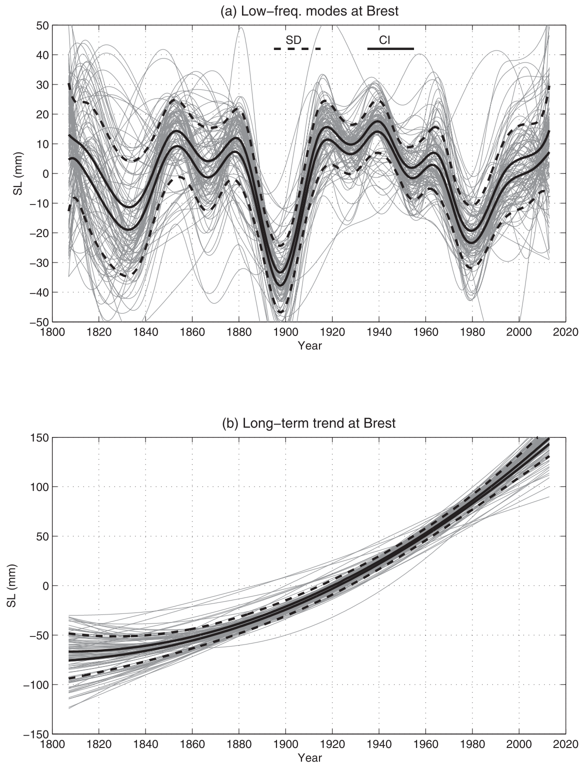


Figure 6. (a) The sum of the three oscillating modes with the lowest frequency, and (b) the trend for sea level at Brest. Gray lines are 100 individual EMD calculations when random white noise is added to the data; heavy, black dashed lines are the standard deviations (SD), and heavy, black solid lines are the 95% confidence intervals (CI) around the ensemble mean. Note that 95% of the individual EMDs are expected to be within the standard deviation lines, whereas there is 95% confidence that the ensemble mean is within the CI range.

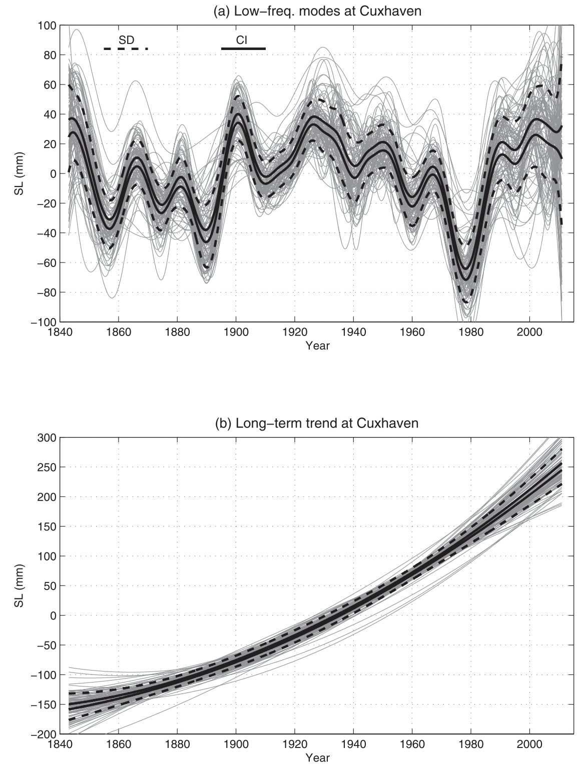


Figure 7. Same as Figure 6, but for sea level at Cuxhaven.

$0.0071 \pm 0.0008$ mm/y$^2$. At Cuxhaven, the low-frequency variability (Figure 7a) is very different in that shallow region than it is at Brest, with a dominant ~20-year period that may relate to local coastal dynamics. Variations in zonal wind are the dominant forcing of the sea level at Cuxhaven, with a lesser effect from atmospheric pressure (Dandendorf *et al.*, 2013). These variations are close in their period to the 18.6-year-long tidal cycle, which can affect high-water events (Gratiot *et al.*, 2008; Haigh, Nicholls, and Wells, 2010). However, the amplitude of the equilibrium, nodal, long-period tide in mean sea level is much smaller than the amplitudes of the oscillations shown here, and according to Woodworth (2011), there is little evidence that the nodal tide contributes significantly to mean sea-level records for European coasts. Oscillations with periods of 15–25 years, as seen in Cuxhaven, Germany, are also found in other locations along the southern coast of the North Sea, such as in Den Helder and Vlissingen, The Netherlands (not shown). The sea-level acceleration at Cuxhaven (Figure 7b) is large and statistically significant ($0.020 \pm 0.004$ mm/y$^2$ from the EMD method and $0.013 \pm 0.003$ mm/y$^2$ with a quadratic fit; Table 1); this acceleration is almost identical to the acceleration previously reported there ($0.012 \pm 0.004$ mm/y$^2$) (Woodworth, Menendez, and Gehrels, 2011). The fact that the nonparametric EMD produces a trend that is so similar in its shape to the quadratic line and with similar mean acceleration provides confidence in the detection of acceleration by the EMD method.

How robust are the decadal and multidecadal variations detected by the EMD analysis?. One of the concerns is about the impact of data gaps (Table 1 lists the percentage of available monthly data). Of the eight stations with long records, five have some gaps—the amount of missing data can be as low as ~2% (Newlyn) or as much as 10% (Brest) or even 30% (Liverpool). The Cuxhaven record is long and complete (100% data availability), so it was used to test the effect of gaps. Four artificial time series were constructed by adding five gaps to the Cuxhaven record and comparing the results with the analysis of the full record. The gaps range from 2–10 year for each gap and 6%–30% missing data, so that in the worst-case scenario the data coverage was quite similar to the real record in Liverpool. The gaps were randomly distributed without overlap. Experiments (not shown) with other scenarios of gap numbers and gap sizes show that the results presented in Figure 8 are quite typical. As expected, increases in missing data resulted in larger errors in the decadal variations, and in particular, gaps as large as 10-year each caused some underestimation in the amplitude and some shifts in the phase (Figure 8a). However, even with gaps as large as 6 year each, the decadal variations were detected by the EMD quite well (root mean square error of ~8 mm compared with a maximum data range of ~100 mm). The effect of the gaps on long-term acceleration (Figure 8b) was small and within the confidence

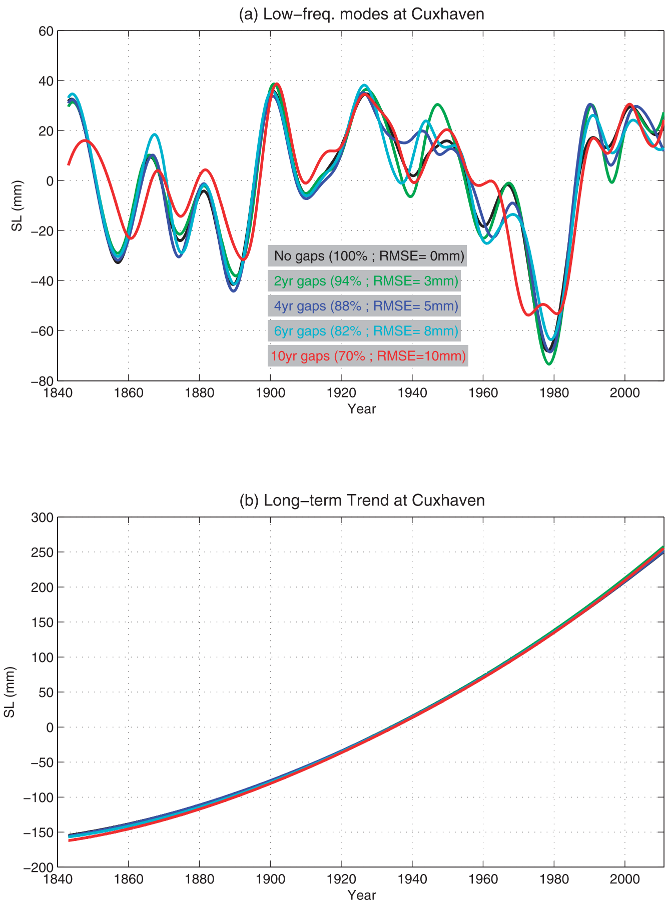


Figure 8. Sensitivity experiments of the effect of gaps in the data on (a) the low-frequency modes, and (b) the long-term trend at Cuxhaven (as in Figure 7). The black line is the original data without gaps, and the color lines are the results with five gaps (randomly distributed without overlap), ranging in size from 2-y gaps to 10-y gaps (∼6%–30% missing data). The root mean square error (RMSE) relative to the case with full data is indicated.

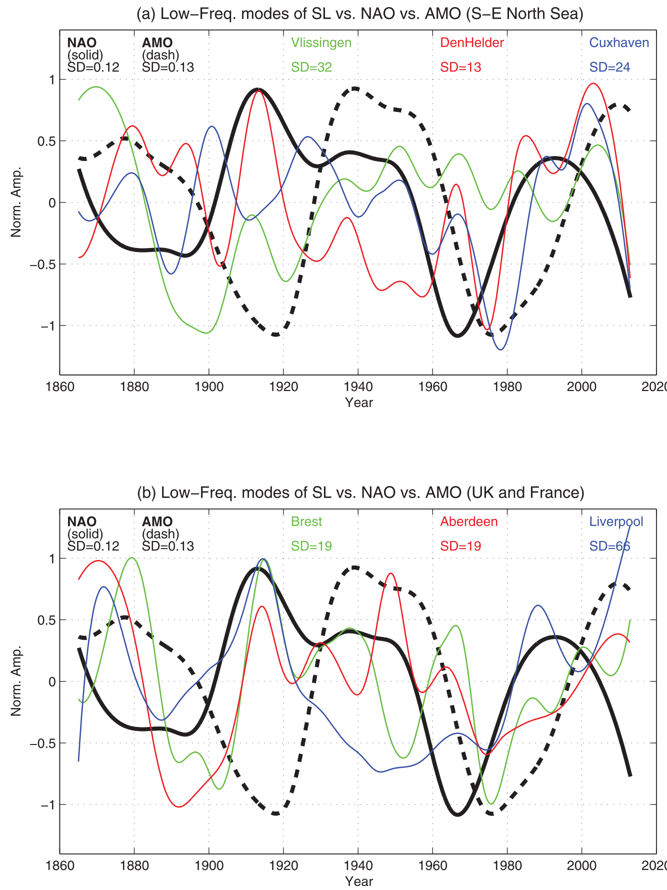


Figure 9. Low-frequency EEMD modes of sea-level records (colored, thin lines) and the climate indexes, NAO (solid, heavy, black line) and AMO (dashed, heavy, black line). Only data for 1865–2012 where used. The amplitude is normalized by the standard deviation, which is listed for each record (NAO and AMO have no units; sea level is in mm). Sea level is geographically divided into (a) stations on the SE coasts of the North Sea, and (b) stations on the coasts of U.K. and France (see Figure 1).

interval of the acceleration (Table 1), demonstrating that EMD-derived acceleration is robust. The effect of gaps on regression analyses will require further studies.

## Influence of NAO and AMO on Sea-Level Variations

Several studies have shown that the long-term oscillations in sea level in the study area, such as those presented here, are correlated with climate indexes, such as the AMO (Enfield, Mestas-Nunez, and Trimble, 2001) and NAO (more precisely, the wintertime NAO; Hurrel, 1995). The exact mechanism by which climate indexes are related to sea level is not completely understood because sea level is complex, is regionally dependent, and involves variations in both pressure and wind patterns (Chen *et al.*, 2014; Dangendorf *et al.*, 2014; Tsimplis *et al.*, 2005a, 2013; Wakelin *et al.*, 2003; Woodworth *et al.*, 2009a,b). Although the NAO represents the differences in atmospheric pressures across the NE Atlantic, which influence the jet stream and the weather patterns, the AMO represents mean sea-surface temperature (SST) over the North Atlantic and is associated, for example, with changes in rainfall and droughts. The AMO can cause coherent multidecadal variations in North Atlantic sea level (Frankcombe and Dijkstra, 2009). Large fraction of decadal variability in sea level on eastern North Atlantic coasts may be explained by nonlocal responses to wind forcing and boundary waves (Calafat, Chambers, and Tsimplis, 2012; Sturges and Douglas, 2011). The two indexes, NAO and AMO, are not independent of each other because both are part of the ocean–atmosphere–earth system (*e.g.,* see Wanner *et al*. [2001] for a review of the relationship between climate indexes and the results of North Atlantic Ocean measurements). Monthly values of the two indexes were obtained for 1865–2012, and the long-term oscillations were extracted using the three lowest-frequency EEMD modes, as done before for sea-level data (they represent variations with periods of ∼20–30 y and longer). Figure 9a compares the climate indexes with sea-level stations from the SE coasts of the North Sea, and Figure 9b compares them with the other sea-level stations from the U.K. and France (Brest). From the mid-19th century to the mid-20th century, the AMO and the NAO are in exactly opposite phases (∼50-y shift in phase), but during the past 60–80 years, the AMO seems to lead

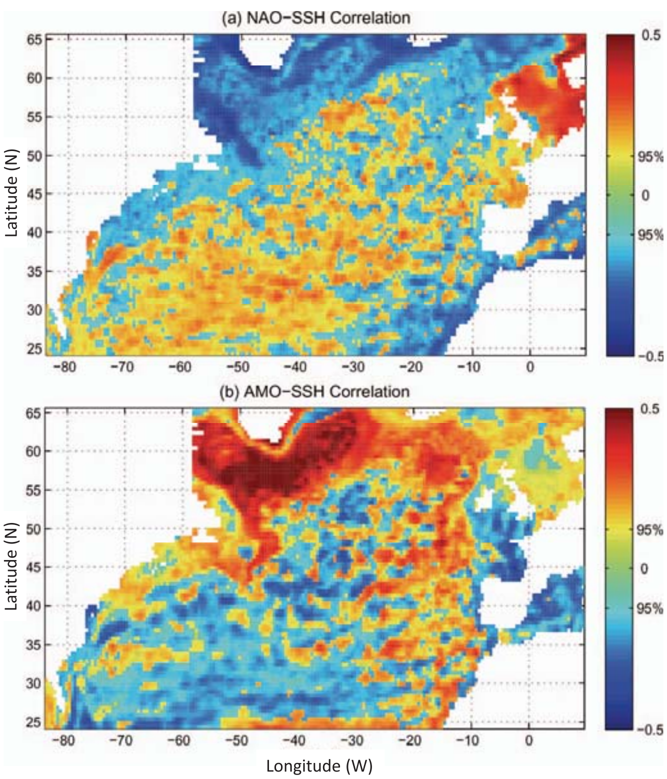


Figure 10. Correlation between the monthly North Atlantic sea surface height (SSH) anomaly obtained from altimeter data (1993–2013) and (a) the NAO index, and (b) the AMO index. The annual cycle and the linear trend have been removed from the data. Shown is the maximum correlation at each ¼° × ¼° box for lag difference less than 20 mo. Estimated 95% confidence interval in the linear regression is indicated on the colorbar.

the NAO by ~10 years. Some coherent positive sea-level anomalies are seen during periods when the AMO and NAO are in opposite phases, for example, in 1870–1880 and 1910–1920. Note, however, that variations in sea level at Cuxhaven (Figure 9a) are often different than at other locations, for example, in 1910 a negative peak was in the opposite phase as that shown in all the other five records. Around the end of the 1970s, when a cooling trend was observed in the subtropical Atlantic and the data in both indexes were negative, all sea-level records show negative anomalies. A high, positive NAO is characterized by stronger westerly winds, which would have an opposite effect on the different sides of the North Sea (Wakelin *et al.*, 2003). Wakelin et al. (2003) also noted a shift in the correlation between NAO and sea level on the NW European coasts, with higher correlations in recent years and lower correlations near the beginning of the 20th century. Therefore, it is possible that some periods are more strongly affected by the AMO (through steric effects of warming/cooling), whereas other periods are more strongly affected by the NAO (through variations in wind and atmospheric pressure). The impact of the climate indexes on sea level interpretation in this region is largely location-dependent, making a cause and effect generalization very difficult. In any case, sea-level records alone cannot fully explain the combined effect of NAO and AMO on the data, so coupled ocean–atmosphere climate models may be needed to further explore the connections, which is beyond the scope of this study.

To see how the sea-level pattern away from the coasts may have changed, sea surface height (SSH) from altimeter data (obtained from AVISO; http://www.aviso.altimetry.fr/) is analyzed. Note that satellite altimeter data are only available from 1993, so they cannot be compared directly with the longer records discussed before.

The NAO and AMO represent large-scale variations that influence the entire North Atlantic Ocean, beyond the study area. Therefore, the correlations between NAO and AMO indexes and the SSH anomaly (the mean SSH, seasonal variations and linear trend have been removed) in the North Atlantic Ocean are shown in Figure 10. The sea-levels variations in the North Sea and along the Norwegian coast have the largest positive correlation with the NAO than any other region in the North Atlantic Ocean, whereas negative correlations are found along the N and W boundaries of the Atlantic (Figure 10a). Although the AMO index is also positively correlated with the SSH anomaly in the NE Atlantic, its largest influence is from the subpolar gyre and the Labrador Sea (Figure 10b), where the NAO and AMO seem to have an opposite impact on sea level. The AMO has an opposite impact on the two sides of the British Isles, which may explain some of the patterns in Figure 9. For example, in the 1950s, when the NAO was close to its mean (with relative less influence), but the AMO was largely positive, Liverpool and Brest on the Atlantic side were at minima sea levels, whereas Aberdeen on the North Sea side had maxima sea levels. In fact, in Figure 9, low-frequency modes of sea level in Liverpool had a correlation (without lag) of +0.3 with the NAO and –0.3 with the AMO. Most other stations in the North Sea had positive correlations with both the NAO and AMO, with correlation coefficients around 0.2–0.4. Therefore, the pattern of correlations seen in the altimeter data during the past 20 years (Figure 10) is generally consistent with the pattern of correlations seen in the tide gauge data during much longer periods (Figure 9).

## DISCUSSION

The difficulty in separating long-term variability from linear and nonlinear trends and, especially, in detecting acceleration in sea levels globally (Church and White, 2006, 2011; Houston and Dean, 2011; Woodworth, Menendez, and Gehrels, 2011; Woodworth *et al.*, 2009a) and regionally (Haigh, Nicholls, and Wells, 2009, 2014; Wahl *et al.*, 2013; Woodworth *et al.*, 1999, 2009b) motivated this study. Therefore, the study focused on two aspects of analysis and understanding of long-term variability in sea level. First, the study introduced a nonparametric analysis tool (EEMD; Wu and Huang, 2009) for studying nonlinear variability in sea-level data. In particular, a new way to estimate errors in acceleration of sea level using ensemble simulations was tested and compared with more-commonly used regression methods. Then, the EEMD analysis was used to study low-frequency sea-level oscillations on western European coasts and to relate the sea-level variability to climate indexes, such as the NAO and AMO. The first part allows a comparison of different analysis methods, whereas the second part allows a comparison of the study area with global acceleration and SLR patterns in other regions, such as coasts on the western side of the North Atlantic Ocean.

Sea-level rise and acceleration along the western coasts of the North Atlantic Ocean (Boon, 2012; Ezer, 2013, 2015; Ezer and Corlett, 2012; Ezer *et al*., 2013; Kopp 2013; Sallenger, Doran, and Howd, 2012; Yin and Goddard 2013) shows a distinctly different pattern N and S of the separation point of the GS at Cape Hatteras, suggesting that ocean dynamics (*e.g.,* changes in the AMOC and the GS) contribute to sea-level variability and sea level rise along the U.S. East Coast. On interannual timescales, shelf wind–driven forcing may also contribute significantly to the pattern of sea level along those coasts (Woodworth *et al*., 2014). By comparison, it is more challenging to find a clear pattern in sea level and to detect acceleration along the eastern coasts of the North Atlantic Ocean (U.K. and western European coasts). In addition to the influence from climatic changes in the North Atlantic Ocean, local coastal ocean processes and spatially varying weather patterns affect sea levels around the British Isles, the North Sea, and western European coasts. Therefore, the EMD analysis that has previously helped to detect sea-level acceleration and variability along the U.S. East Coast (Ezer, 2013, 2015; Ezer and Corlett, 2012; Ezer *et al*., 2013) is used here for analysis of very long (~100-200 y) tidal gauge records from the U.K. and western European stations. Because this method is relatively new, it is compared with a more-traditional method of regression analysis that fit the data (using a least-squares method) with a quadratic trend line. There is no reason to expect that sea level trends will follow a specific type of predetermined line, such as a linear trend or a quadratic trend (which is the simplest acceleration model of a polynomial fit). Therefore, the nonparametric EMD analysis provides a more-general approach to studying nonlinear sea-level trends, without assuming that the record will follow a particular line, as in Equation (4). Despite the very different analysis methods, the sea-level accelerations obtained by the two methods was very similar, providing more trust in the results. It was demonstrated here how the EMD analysis can be used to separate oscillating modes from nonlinear trends and to help to connect between long-term oscillations in sea level and climate indexes. Another new result demonstrated here was the usage of the EMD to evaluate the effect of data gaps; gaps can cause concern and difficulty in any analysis method that tries to identify periodic cycles in data.

## CONCLUSIONS

The nonlinear, long-term trends from the longest records show positive sea-level accelerations with an average value during the past ~150 years of 0.014 $\pm$ 0.003 mm/y$^2$ from standard quadratic regression and 0.012 $\pm$ 0.004 mm/y$^2$ from the new EMD analysis (Table 1). This acceleration is similar to estimates of global acceleration (0.011 $\pm$ 0.004 mm/y$^2$; Church and White, 2011). An outlier was the record in North Shields, which provided further evidence that the datum at that station has changed after a long gap, as previously suggested by Woodworth (1999). Another interesting result was that two shorter records of ~70 years (Dublin and Southampton), which show greater acceleration (~0.1 mm/y$^2$, similar to acceleration found along the U.S. East Coast; Ezer, 2013) than do the longer records. This may indicate a recent increase in acceleration, or the effect of unresolved long cycles; further research with more data is thus needed. Because some studies questioned the accuracy of detecting sea-level acceleration using the EMD residual or even other methods (Chambers, 2015; Haigh *et al*., 2014; Kenigson and Han, 2014; Visser, Dangendorf, and Peterson, 2015), the EMD-derived acceleration was compared here with a standard quadratic fitting method, showing extremely good comparisons (Figure 2; Table 1). The results are quite robust even when considerable gaps (2–6 y long each) in the data exist, as long as the gaps are shorter than the period of the detected cycles. The EMD analysis demonstrated how analysis of sea-level variations with long periods is influenced by climate indexes, such as the NAO and AMO. Complicating the distinction between the impact of the NAO (possibly through wind and pressure effects) and AMO (possibly through steric and precipitation effects) is the fact that NAO and AMO were anticorrelated with each other in the past, but the phase difference between them has shifted over time. Thus, it is possible that, at some period, sea levels were more affected by the NAO whereas, at another period, the AMO is a more-dominant influence. Analysis of the spatial pattern in the SSH anomaly, obtained from altimeter data, reveals that the North Sea and the Norwegian coast are more influenced by the NAO than any other region in the North Atlantic Ocean, and the sea-level response there is opposite to that on the western North Atlantic. The analysis presented here demonstrates that local variations of coastal sea level cannot be studied solely as a local phenomenon but must be considered as part of large-scale climatic changes of the whole North Atlantic Ocean. For the long records considered here, there is little doubt that there is positive acceleration in this region, and it is likely related to global sea-level acceleration. This result is important for future sea-level projections because accelerating SLR is directly related to accelerating flooding in low-lying areas (Ezer and Atkinson, 2014).

## ACKNOWLEDGMENTS

Old Dominion University's Climate Change and Sea-level Rise Initiative (CCSLRI) provided partial support for this study. Part of the study was conducted when T.E. was a visiting scientist at the National Oceanography Centre (NOC) and the University of Southampton, U.K., so NOC and many of its scientists are thanked for providing facilities and interesting discussions that helped in this study. I.D.H time was partially covered through the U.K. Natural Environment Research Council consortium project iGlass (NE/I009906/1; I.D.H). Four reviewers provided many useful suggestions that helped to improve the manuscript.

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