Continental Shelf Research 148 (2017) 44–52

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Analysis of tidal amplitude changes using the EMD method

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ARTICLE INFO

Keywords:
Tide
EMD
Harmonic analysis
Sea level

ABSTRACT

Empirical Mode Decomposition (EMD) analysis of sea level data has been used in the past mostly to study long-term sea level rise (SLR) and decadal/multidecadal variations. However, application of EMD to high-frequency sea level variability is rare, so here EMD is tested as a tool to analyze hourly sea level data and detect time-dependent changes in tidal characteristics. Traditional Harmonic Analysis (HA) cannot deal with non-linear, non-stationary processes such as storm surges. Here, the two methods are compared in the analysis of 17 tide gauge records from the U.S. East Coast, demonstrating considerable trends and interannual variability in the semidiurnal tides. The time dependent changes of tidal characteristics are unique for each region and in some cases for specific locations. The results show that in most stations the highest and second-highest frequency modes of the EMD can capture the semidiurnal and diurnal tides, respectively. High correlation is often found between the variations of the first EMD mode and the amplitude of the M_2 tide obtained from HA. However, in some locations the high frequency EMD mode captures other (non M_2) variability and in other locations a sudden shift in tidal characteristics is found. In Baltimore for example, during the 1970s the amplitude suddenly increased for the M_2 tide but decreased for the S_2 tide, and in Wilmington a significant increase (~ 20 cm in ~ 80 years) in the amplitude of the M_2 tide is detected by both methods. These changes could indicate an instrumental change or a morphological change due to storm surges. This short report is meant to demonstrate a new tidal analysis tool that can help studies of changes in tidal characteristics and the relation of these changes to morphology change, sea level rise and climate change.

1. Introduction

The U.S. Northeastern coast has been identified as a 'hotspot' of accelerated sea level rise (SLR, Ezer and Corlett, 2012; Sallenger et al., 2012) and accelerated flooding (Ezer and Atkinson, 2014). The region shows a significantly higher SLR trend than global mean SLR (Church and White, 2011; Houston and Dean, 2011). This is due to a combination of land subsidence and potential slowdown of the Atlantic Meridional Overturning Circulation (AMOC) and a weakening of the Gulf Stream (GS) flow (Ezer, 2015; Ezer et al., 2013). Over time, SLR increases the damage to low-lying coastal communities during storm surges (Tebaldi et al., 2012; Wahl et al., 2014; Wahl and Chambers, 2016; Wdowinski et al., 2016) and increases the frequency of minor tidal flooding (Sweet and Park, 2014). Since minor flooding is related to the combination of SLR and tidal amplitude (Ezer and Atkinson, 2014), it is important to detect any changes in the characteristics of tides over time. Note however, that tidal amplitude itself can also be affected by SLR (e.g., Pickering et al., 2017).

Recent studies have found an increase in the M_2 tidal amplitude in the Gulf of Maine (Ray, 2006, 2009) and along the U.S. East Coast (Woodworth, 2010). Coherent linear trends of tidal range in the last 30–90 years have been reported over the regions (Flick et al., 2003). Müller (2011) pointed out that the physical causes of tide trends and their spatial variability are uncertain and it is difficult to relate them to other oceanic or atmospheric variables, though there are evidences that SLR can affect tides in coastal regions (Pelling et al., 2013). Numerical modeling experiments of the impact of future SLR on tides demonstrate a complex response, so that for the same SLR rate, tidal energy may increase on one coast and decrease in another nearby coast (Lee et al., 2017). Although the land motion due to Glacial Isostatic Adjustment (GIA) and SLR contribute to the trend of tidal amplitudes, numerical simulations have difficulties to reproduce the spatial pattern of the tidal trend (Müller, 2011), since the complicated mechanisms of tidal characteristic changes (Mawdsley et al., 2015). Therefore, changes in tidal characteristics due to SLR and other climatic changes can be very different between one region and another (Woodworth, 2010; Pickering

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http://dx.doi.org/10.1016/j.csr.2017.09.009
Received 11 January 2017; Received in revised form 11 September 2017; Accepted 21 September 2017
Available online 23 September 2017
0278-4343/

et al., 2017).

This study was motivated by the need to better detect changes in the variability of tides which, when combined with uncertainty in SLR, can increase risk of flooding (Greenberg et al., 2012). Low-lying populated regions such as the Hampton Roads in Virginia, Miami Beach in south Florida, and Boston are examples of areas that are especially vulnerable flooding due to SLR (Atkinson et al., 2012; Ray and Foster, 2016; Wdowinski et al., 2016; Zhang, 2011; Zhang and Sheng, 2013).

The common method used to study the changes in tides is harmonic analysis (HA, (Foreman, 1977)), which can be applied for example to hourly sea level records obtained from tide gauges. This work aims to test the feasibility of using Empirical Mode Decomposition (EMD) analysis (Huang et al., 1998; Huang and Wu, 2008) to detect changes in the semidiurnal tide amplitude. This new tidal analysis method could supplement the standard HA. The EMD method is a non-stationary and nonlinear time series analysis method, so that irregular patterns of storm surges, or tidal amplitude changes over time are good test cases for this method. The method decomposes any time series data into a finite number of intrinsic mode functions (oscillating modes) with time-variable amplitudes and frequencies, plus a residual (or trend). EMD has been widely used for analysis of different geophysical data (Wu and Huang, 2009), as well as for other applications such as in seismic, medical and economic data.

In recent years, applications of the EMD method for analysis of sea level data have focused on calculations of SLR trends, SLR acceleration and long-term sea level variability (e.g., Ezer and Corlett, 2012; Bonaduce et al., 2016; Cheng et al., 2016; Ezer, 2013, 2015; Ezer et al., 2016; F. Li et al., 2016; Y. Li et al., 2016), sea level reconstruction (e.g., Sha et al., 2015) and future SLR projections. Note that in the above studies the EMD was used to filter out high-frequency oscillations to discover lower-frequency variations, while here the high-frequency oscillations are the main subject of the research. Therefore, in this new application the EMD is used to analyze high-frequency modes to test if they can describe the variability of the M_2 and other semidiurnal tides (M_2 is the dominant constituent of tides along the U.S. East Coast). Note that because EMD is a non-stationary method, it can detect time-dependent changes in amplitude and frequency with one calculation of an entire record, while the HA will require multiple calculations, each one using small sub-sections of the data (say 1 year) to see if the tidal characteristics change over time. On the other hand, the disadvantage of the EMD is that it is a non-parametric method (frequencies are not specified and oscillations are not assumed to be sinusoidal) and thus it cannot guarantee to extract the known tidal constituents. Therefore, the proposed EMD analysis needs to be tested against standard methods to learn of its usefulness and limitations.

The paper is organized as follows. The tide gauge sea level records and the methodology employed in this study are described in Section 2. The results are presented in Section 3 and the discussion and summary are provided in Section 4.

2. Dataset and methodology

2.1. Tide gauge sea level records

Hourly tide gauge data were obtained from NOAA (http://opendap.co-ops.nos.noaa.gov/dods/). Fig. 1 shows the locations of the selected 17 tide gauges along the U.S. coast. Most stations provide long and continuous sea level records (average starting year ~1917; see Table 1) except 2 stations in the lower Chesapeake Bay starting in the 1970s' (No. 10 and 11). The 2 shorter records are located in a region with significant land subsidence (Kopp, 2013). Our study includes more stations than a previous study of the issue (Müller, 2011).

2.2. Harmonic analysis

The standard tool for tidal analysis is often based on HA. Available software includes for example, TASK (Tidal Analysis Software Kit, Bell et al., 1996), T-tide (Pawlowicz et al., 2002) and Utide (Codiga, 2011). The Utide was selected to calculate all tidal constituents for its capability in solving the nodal cycle with the default settings. Experiments (not shown) with subset windows of 1, 2 or 3 years show very little effect on the results. The HA is applied to hourly data in each year. Then the results of all years provide a time series of the M_2 tidal amplitude which then is compare with that computed from the EMD method (see below).

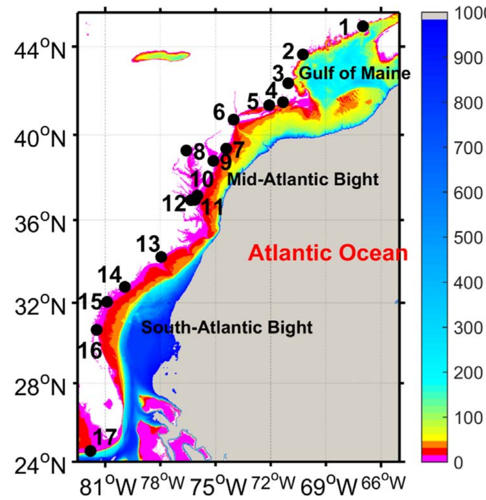

Fig. 1. Bathymetry of the study area and location of the selected tide gauges (the numbers according to the tide gauges listed in Table 1). The regions with water depth larger than 1000 m are marked as grey.

2.3. Empirical mode decomposition

To detect changes in tidal amplitudes, we analyze the high frequency modes obtained for each station using EMD. The EMD of a sea level record from location M would be represented by

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

where N denotes a finite number of oscillating modes, c_i *(t)* is intrinsic oscillatory modes, and *r(t)* is a residual (or "trend"). The number of modes depends on the record length and the amount of variability. The oscillating modes are calculated by a repeated sifting process (a kind of filter) until only the residual is left. A Hilbert spectrum transform is applied for each mode to provide a time-dependent estimation of the frequency of the oscillations (thus EMD is often called a Hilbert-Huang Transform, HHT; Huang et al., 1998). Note that particular modes do not necessarily represent specific processes, but the analysis allows the separation of noisy records into oscillations with different time scales. Statistical confidence levels for EMD modes can be calculated using variations in the sifting parameters (Huang et al., 2003), bootstrap methods (Ezer and Corlett, 2012) or ensemble with white noise simulations (Ezer, 2016). However, no quantitative examination of each mode is done here, only the 1-year average magnitude of the peaks of the highest frequency EMD mode is examined, to test if it is consistent with changed in the dominate M_2 tidal constituent obtained by the HA. More detailed statistical examination is left for future follow up studies. Appendix Fig. A1 shows an example of the 19 EMD modes for station Baltimore (for discussion of the interannual and decadal variability in this and other sea level records, see previous studies such as Ezer (2013, 2015).

For consistency purposes, both the EMD analysis and HA adopt the least-square fitting method in Müller (2011) to determine the linear trend (A). To remove the long-term nodal cycle (amplitude A_N; period