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Subtidal variability of sea level in a macrotidal and convergent estuary

Lauren Ross[a,b,*], Aldo Sottolichio[b]

[a] University of Maine, Civil and Environmental Engineering, 5711 Boardman Hall, Orono, ME, USA
[b] University of Bordeaux, Laboratoire EPOC, Allee Geoffroy St Hilaire, PESSAC, France

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ABSTRACT

Time series (2011 through 2013) of water level elevations measured at nine locations along the Gironde Estuary, on the southwest coast of France, were analyzed to investigate both propagation and forcing mechanisms of tidal and subtidal pulses. A Lanczos low pass filter (35 h) was applied to the three-year time series of water level from each tide gage station and the seasonal signal was removed. Both Regular (REOF) and Complex Empirical Orthogonal Function (CEOF) analyses were applied to the detrended water level to provide information on the spatial and temporal structure of the subtidal pulses. The explained variance of the first two dominant modes from both the REOF and CEOF analyses together explained 98% of the variance, with the first mode explaining ~90% and the second, ~8%. The spatial structure of the first two modes both showed amplitude amplification (0.2 cm/km for the first mode and 1 cm/km for the second) over the entire length of the estuary. A local phase minimum, derived from the CEOF analysis, was found at the mouth of the estuary for mode 1 and at the head of the estuary for mode 2. This indicated that the first mode was forced by coastal processes and the second mode by upstream (riverine) mechanisms. A numerical model of the Gironde estuary was used to help understand the forcing mechanism behind REOF and CEOF mode 1. The results of a numerical model simulation forced only with tides was compared to the spatial structure of the dominant REOF and CEOF mode, and verified that mode 1 was a product of tidal processes. The second mode resulted from variations in river flow linked to synoptic weather patterns.

1. Introduction

Barotropic tidal motions produce the majority of the energy found in tidally dominated estuaries. In these estuaries, instantaneous currents are controlled by the barotropic tide, but the transport and dispersion of salt, pollutants, plankton and other waterborne materials are driven primarily by the residual flow (McCarthy, 1993). The transport of salt by residual currents, which is linked to salt intrusion into estuaries, is becoming an increasingly important topic as a result of imminent sea level rise. Multiple studies have shown that variations in subtidal water level is directly linked to salt intrusion into estuaries (Sucsy and Morris, 2001; Sucsy and Morris, 2002; Henrie and Valle-Levinson, 2014). Further, it has been found in some estuarine systems that the impact of subtidal forcing on water level variability exceeds that of tidal forcing (Bacopoulos et al., 2009). Therefore, subtidal variations in water level can provide information on salt intrusion length scales and a glimpse into the future effects of sea level rise on a given system.

Henrie and Valle-Levinson (2014) found that subtidal pulses in a subtropical estuary behaved as damped waves that propagated 145 km upstream. Further, the subtidal wave propagation was dependent on basin geometry and the frictional properties of the system. However, this study only included one year of water level elevation data from multiple locations along the estuary under consideration. Therefore, the authors could not determine if the subtidal dynamics found in their study were typical of the region or happenstance. Other studies carried out in highly frictional environments likened tidal waves to diffusive processes rather than propagating long waves (Friedrichs and Madsen, 1992; Waterhouse et al., 2011). Analytical (theoretical) models have been used to recreate subtidal water level elevations in both tidally dominated and convergent estuaries (Friedrichs and Aubrey, 1994; Li and O'Donnell, 2005). In particular, Li and O'Donnell (2005) developed a two-dimensional (depth-averaged) analytical model to describe residual flow in tidally-dominated systems. However, their model assumes a rectangular basin shape, and therefore can not accurately capture subtidal dynamics in funnel-shaped basins.

The one-dimensional (depth and width-averaged) analytical model developed by Friedrichs and Aubrey (1994) captures the width convergence effects of many real estuaries, however it was developed based on a 90° phase difference between tidal velocity and elevation of the

* Corresponding author at: University of Maine, Civil and Environmental Engineering, 5711 Boardman Hall, Orono, ME, USA.
E-mail addresses: lauren.ross1@maine.edu (L. Ross), aldo.sottolichio@u-bordeaux.fr (A. Sottolichio).

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semidiurnal tide (period of 12.42 h). This implies that tidal elevation of the fourth-diurnal is generated (period of 6.21 h), but no set-up of water level presumes, so the systems considered in their work are ideal or equilibrium estuaries. Savenije et al. (2008) derived one-dimensional analytical solutions to understand tidal dynamics in convergent channels, which was not restricted to the equilibrium estuary assumption made by Friedrichs and Aubrey (1994). Although these equations broaden the range of funnel-shaped estuaries that can be accurately modeled analytically and provide a simple way to detemine characteristics of a convergent system, it remains that many assumptions are needed in order to maintain the analyticity of the equations. In particular, Savenije et al. (2008) assume that the tidal wave can be described by a simple harmonic function. However, it is well-known that in strongly convergent channels the tidal wave deforms as it propagates upstream. Numerical models have proven to be valuable tools in understanding tidal and residual processes in estuaries, in that they can accurately capture details of the estuary shape and tidal characteristics. They have also been used to study the subtidal characteristics of many estuarine systems (de Jonge, 1992; O'Connor, 1991; Brooks et al., 1999; Warner et al., 2005; Liu et al., 2007).

This study aims to determine the wave properties and forcing mechanisms behind tidal and subtidal pulses in a macrotidal and convergent estuary. In particular, water level variability is investigated in the Gironde Estuary, on the southwest coast of France. The Gironde is a prototypical hypersynchronous estuary and is therefore a natural laboratory to better understand tidal and subtidal water level variations in other similar systems. In addition, water level elevation data used in this study spans three years at multiple locations along the estuary. Statistical analyses, which include Regular and Complex Empirical Orthogonal Function analyses are applied to water level data to determine dominant modes of variability. The results of the statistical analysis are compared to a numerical model simulation as well as wind and river discharge measurements to determine the forcing mechanisms behind subtidal variability of water level in the Gironde. To date, measurements of subtidal water level variations have not been analyzed in the Gironde Estuary, or to this extent in other tidally dominated environments around the world.

Further, the Gironde is the largest estuary in all of Western Europe and therefore has significant economic and ecologic importance. Despite this, the fundamental dynamics of this system are not well known. This study expands the knowledge base of the Gironde by describing the behavior and forcing mechanisms driving tidal and subtidal water level elevation in this system for the first time.

2. Study area

The Gironde is a macrotidal estuary located on the southwest coast of France. It extends from the Atlantic coast 75 km inland to the confluence of the Garonne and Dordogne Rivers and covers a surface area of 635 km^2, making it the largest estuary in all of Western Europe (Sottolichio et al., 2011; Jalón-Rojas et al., 2015). The width of the estuary varies from 11.3 km near the mouth to 3.2 km at the confluence zone of the Garonne and Dordogne Rivers (Fig. 1) (Huybrechts et al., 2012). Although the estuary is 75 km long, the tidal wave propagates 180 km from the estuary mouth. In particular, it reaches 95 km up the Garonne River and 90 km up the Dordogne River (Bonneton et al., 2015). The Garonne and Dordogne rivers feed into the Gironde estuary with combined discharge values ranging from 50 to 2000 $m^3\,s^{-1}$, and flood events with discharge exceeding 5000 $m^3\,s^{-1}$ (Huybrechts et al., 2012).

The tide is mainly semidiurnal with amplitudes at the mouth ranging from ~2.5 to 5 m on a neap/spring cycle (Bonneton et al., 2015). As the tide propagates upstream it becomes asymmetric and flood-dominant, typically displaying 4 h for flood and 8 h 25 min for ebb (spring tides at Bordeaux, Fig. 2). In addition, the Gironde experiences coastline convergence and is hypersynchronous, meaning that convergence effects exceed that of frictional effects and therefore tidal currents are amplified toward the head of the estuary.

3. Data

3.1. Collection

Hourly water level data provided by the Bordeaux Harbour Authority (GPMB) were collected from nine tide gage stations along the Gironde estuary for three consecutive years (2011, 2012 and 2013). The hourly water level measurements were collected relative to the mean sea level from the mouth to the head of the estuary at Port Bloc (PB), Richard (R), Lamena (L), Pauillac (P), Fort Medoc (FM), Ambes (A), Le Marquis (LM), Bassens (B) and Bordeaux (BO) (Fig. 1). The detailed locations for each of these stations can be found in Table 1. It should be noted that the stations from Port Bloc to Ambes are within the Gironde Estuary and the stations from Le Marquis to Bordeaux are in the Garonne River. A representative day of water level variations at each of the 9 tide gage stations during neap and spring tides are shown in Fig. 2. Daily river discharge measurements supplied by French governmental agencies (data available at data.eaufrance.fr) for both the Garonne and Dordogne Rivers were collected for the same three years as the tidal data. Wind data were available only for 2012 at the Bordeaux airport (44°50′N, 0°42′W), therefore these data are only used to provide a general idea of the wind regime in the region over 12 months during the data collection period.

3.2. Processing

3.2.1. Water level elevations

A *t tide* analysis adapted from Pawlowicz et al. (2002) was applied to each of the nine water level time series (in intervals of 100 days) to determine the dominant harmonic constituents in the Gironde (Fig. 3). The subtidal water level was obtained by applying a Lanczos low-pass filter of 35 h to each of the nine tidal time series. To remove the seasonal variability, a Lanczos low-pass filter of 45 days was applied to the water level data at each of the tide gage stations as done in Henrie and Valle-Levinson (2014). The seasonal variability was then removed (subtracted) from the subtidal water level at each station and the resulting time series will be referred to as the detrended water level elevations (Fig. 4). To better visualize the along-channel variations of the subtidal water level throughout time, a contour of the subtidal variations from the year 2013 were plotted against distance along the estuary (Fig. 5).

3.2.2. Regular and complex EOF

Regular Empirical Orthogonal Function (REOF) analysis was used to extract dominant spatial modes (or patterns) from time series of detrended water level elevation data collected at multiple locations along the Gironde estuary. REOF analysis is a tool used for identifying signals that involve changes that occur simultaneously at multiple locations. However, it is less effective at identifying propagating modes (Emery and Thomson, 2014).

Complex Empirical Orthogonal Function (CEOF) analysis was used to determine the space/time scales and wave propagation information from along-estuary subtidal water level variations in the Gironde. This statistical analysis allowed for easy investigation into the dynamic behavior of energetic events found in the system (Barnett, 1983). The complex (or Hilbert) EOF converts the sea level data (w) into a complex form (W) by including the Hilbert transform ($\hat{w}$) of the original time series. Therefore, the complex data varying in space and time ($W = w + i\hat{w}$) can provide both amplitude and phase information. As explained in Henrie and Valle-Levinson (2014), the CEOF analysis provides information on three different aspects of the subtidal pulses. First, the along-channel distribution of the subtidal pulses. Second, phase propagation of the along-channel distribution of the