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Comparison of environmental forcings affecting suspended sediments variability in two macrotidal, highly-turbid estuaries

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ABSTRACT

The relative contribution of environmental forcing frequencies on turbidity variability is, for the first time, quantified at seasonal and multiannual time scales in tidal estuarine systems. With a decade of high-frequency, multi-site turbidity monitoring, the two nearby, macrotidal and highly-turbid Gironde and Loire estuaries (west France) are excellent natural laboratories for this purpose. Singular Spectrum Analyses, combined with Lomb-Scargle periodograms and Wavelet Transforms, were applied to the continuous multiannual turbidity time series. Frequencies of the main environmental factors affecting turbidity were identified: hydrological regime (high versus low river discharges), river flow variability, tidal range, tidal cycles, and turbulence. Their relative influences show similar patterns in both estuaries and depend on the estuarine region (lower or upper estuary) and the time scale (multiannual or seasonal). On the multiannual time scale, the relative contribution of tidal frequencies (tidal cycles and range) to turbidity variability decreases up-estuary from 68% to 47%, while the influence of river flow frequencies increases from 3% to 42%. On the seasonal time scale, the relative influence of forcings frequencies remains almost constant in the lower estuary, dominated by tidal frequencies (60% and 30% for tidal cycles and tidal range, respectively); in the upper reaches, it is variable depending on hydrological regime, even if tidal frequencies are responsible for up 50% of turbidity variance. These quantifications show the potential of combined spectral analyses to compare the behavior of suspended sediment in tidal estuaries throughout the world and to evaluate long-term changes in environmental forcings, especially in a context of global change. The relevance of this approach to compare nearby and overseas systems and to support management strategies is discussed (e.g., selection of effective operation frequencies/regions, prediction of the most affected regions by the implementation of operational management plans).

1. Introduction

Dynamics of estuarine suspended particulate matter (SPM) are complex and strongly variable over time scales ranging from seconds to years. SPM distribution in the water column results from the balance between erosion, transport and deposition processes, which are modulated by the combination of multiple controlling forces (Dyer, 1988). Understanding the variability of SPM requires a good knowledge of these forcings and of their interactions at all the significant time scales. In tidal estuaries, the analysis of factors influencing fine sediment dynamics is often related to the identification of mechanisms causing turbidity maximum zones (TMZ; Allen et al., 1980; Dyer, 1988; Talke et al., 2009). Subsequently, most works have mainly addressed the response of the TMZs to changes of the main forcings, such as river flow and tidal range (Uncles and Stephens, 1993; Fettweis et al., 2012; Grabemann et al., 1997; Uncles et al., 2006; Jalón-Rojas et al., 2015, 2016b).

The identification of environmental factors affecting turbidity rarely includes a consistent evaluation of their relative contribution to SPM variability that considers the spatial and temporal dimensions. These latter aspects are particularly important as estuaries are dynamic ecosystems where environmental forcings are not in steady state but evolve under the effect of climate change (Pugh, 2004; Alfieri et al., 2015) and human activities (Winterwerp

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and Wang., 2013; Uncles et al., 2013). Knowing the influence of forcings in different regions of an estuary is imperative to better understand the behavior of these systems, but also to anticipate their response to environmental changes or human interventions. The quantification of the forcings influence with time is a key issue prior to any evaluation of the response of estuarine systems to long-term changes.

Environmental forcings affecting SPM in coastal systems are relatively well known. They involve deterministic (tidal cycles, tidal range) and stochastic (river flow, wind, turbulence) components (Schmitt et al., 2008) that result in multiscale, non-stationary and nonlinear dynamics. Quantifying the contribution of each forcing to turbidity variability is then a complex task that has been barely explored. Two studies carried out in the San Francisco Bay and the Blyth Estuary (Schoellhamer, 2002; French et al., 2008) quantified turbidity variability at time scales related to environmental forcings. In both cases, Singular Spectrum Analysis (SSA; Schoellhamer, 2001) was applied to high-frequency SPM concentration time series, but these analyses were spatially limited to a single cross section of each system. The scarcity of long-term high-frequency time series is probably responsible for the lack of such quantitative analysis. In fact, long-term, multi-site SPM monitoring requires substantial effort and is still not very common in estuaries (Jalón-Rojas et al., 2016b).

The Gironde and Loire estuaries are quite unique in having a continuous monitoring of turbidity for about a decade. These macrotidal and highly-turbid estuaries are geographically very close and drain the two main French watersheds to the Bay of Biscay. A well-developed TMZ, characterized by SPM concentrations higher than 1 g l^{-1} in surface waters, is a well-known feature in the Loire (Gallenne, 1974; Jalón-Rojas et al., 2016b) and in the Gironde (Allen and Castaing, 1973; Jalón-Rojas et al., 2015). Thanks to high frequency monitoring, the SPM dynamics are now well documented in these two estuaries, from intratidal to interannual time-scales (Jalón-Rojas et al., 2015, 2016b). The Gironde and the Loire estuaries are then two excellent natural laboratories to evaluate the relative impact of forcings on SPM. Furthermore, the comparison of these two nearby estuaries is of great interest in order to further understand the common behavior of suspended sediments.

The objective of this work is to quantify the turbidity variability at time scales characteristic of environmental forcings in macrotidal estuaries. For this purpose, we combine different spectral methods to analyze the high-frequency multiannual turbidity time series recorded in the Gironde and the Loire estuaries. The specific aim is to estimate and compare the relative contributions of the main identified forcings frequencies on turbidity at seasonal and multiannual time scales and in different estuarine regions of these two estuaries. This approach allow: (a) to detail the variability time scales of turbidity beyond the classical qualitative analysis; and (b) to compare patterns in nearby, but also distant overseas, tidal systems; and (c) to evaluate the consequences of changes in forcings on turbidity variability.

2. The study sites

The Loire and the Gironde are two macrotidal fluvial-estuarine systems located on the Atlantic French coast (Fig. 1). Their main morphological and hydrological characteristics are summarized in Table 1.

With respective surface areas of 635 km^2 and 102 km^2, the Gironde and the Loire estuaries are the two largest French estuaries. The Loire has a single riverine channel showing a funnel-shape in the outer estuary (Fig. 1A). The mean depth of its navigation channel, which is permanently dredged, is about 5.5 m between Donges and Trentemoult (Table 1, Cheviet et al., 2002). The Gironde Estuary is funnel-shaped between the mouth and the junction of two tidal rivers (the Garonne and the Dordogne Rivers, Fig. 1B). Downstream the junction, the estuary has two main channels separated by elongated sand banks and shoals. The left bank channel is permanently dredged for navigation to maintain a minimum depth of 8 m at low tide. The right-bank channel evolves naturally and presents a mean depth of about 5 m.

Tides are semidiurnal and have similar tidal ranges at the two mouths (Table 1). The tidal waves propagate up to 100 km and 180 km from the mouth in the Loire and the Gironde, respectively, where they are completely damped by friction. During their upstream propagation, tides become increasingly asymmetrical (flood shorter than ebb) and the wave is amplified (Allen et al., 1980; Le Hir and Thouvenin, 1994). The highest tidal range, about 6.3 m, is reached between 26 and 52 km (from the mouth) for the Loire (Jalón-Rojas et al., 2016b) and between 100 and 126 km for the Gironde (Castaing et al., 2006) (Table 1). The tidal wave starts to damp around 52 and 130 km (from the mouth) for the Loire and Gironde, respectively.

The Loire and the Gironde drain the two largest French watersheds, covering together one third of the French territory (Fig. 1C, Table 1). The Loire daily-mean discharge is equivalent to the sum of the Garonne and Dordogne inputs to the Gironde (Table 1). In both estuaries the minimum and maximum values are measured during the periods comprised between July–September and December–February, respectively. In addition, the Garonne River has a second period of high river discharge between April and May due to snow melting in the Pyrenees. Over the last decade, the driest and wettest years were 2011 and 2013, respectively. There are water abstractions in both watersheds, particularly to sustain discharge during summer, but the Garonne and the Dordogne Rivers have the highest number of reservoirs and a storage capacity about five times higher than that of the Loire (Table 1). The variability in hydrology over the last decades is quite similar for the Gironde and the Loire (Chevalier et al., 2014). These watersheds show a trend in decreasing river flow induced by climate change and land use (Boé et al., 2009).

In both systems, the asymmetry of the tidal wave, when propagating upstream, coupled to density residual circulation creates a pronounced TMZ (suspended sediment concentrations > 1 gl^{-1}, Allen et al., 1980). The Gironde estuary is known for a naturally well-developed TMZ (Castaing and Allen, 1981), even if there is no fully reliable reference state before the 1970's. For the Loire estuary, there is evidence that its current hyperturbid state was more recently reached, largely due to continuous artificial modifications of its morphology during the last two centuries, which progressively favored the flood-dominant conditions (Winterwerp and Wang, 2013). One could refer to Jalón-Rojas et al. (2015; 2016b) for a detailed description of turbidity and TMZ dynamics from tidal to multi-annual time scales in the Gironde and the Loire estuaries.

3. Materials and methods

3.1. The monitoring systems

The Loire and the Gironde estuaries have each an automated, high-frequency, long-term monitoring network of water quality, called SYVEL (SYstème de Veille dans l'Estuaire de la Loire) and MAGEST (MArel Gironde ESTuary), respectively. SYVEL includes six stations distributed from the mouth up to 62 km upstream (Fig. 1A). This network was implemented in 2007, except the station of Donges that was added in December 2010. Cordemais station was stopped in December 2011. It must be noted that the