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Analysis of stratification patterns in river-influenced mesotidal and macrotidal estuaries using 3D hydrodynamic modelling and K-means clustering

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ABSTRACT

A methodology to determine the spatial and temporal evolution of stratification in estuaries driven by astronomical tides and river discharges was developed and is presented here. Using a 3D hydrodynamic model, the variation of estuarine currents, water levels and densities was investigated under different realistic forcing conditions. These conditions were classified from a long-term period (>30 years) of river flows and tidal water levels by a K-means clustering approach suggested by Bárcena et al. (2015). The methodology allows computing the location of mixed, partially mixed/stratified and stratified areas in tidal river estuaries along a continuum by means of Richardson's Layer number and the frequency of every model scenario. In order to illustrate the power of the method, it was applied to a case study, the Suances Estuary. In the application case, the Suances Estuary was vertically mixed at its innermost part due to riverine influence. At the outer part, it was also vertically mixed due to the turbulence caused by tidal action. At the intermediate section, it was partially mixed in the main channel or stratified in intertidal areas due to the combined action of forcing, depth gradients between the main channel and intertidal areas, and salinity variations in the water column.

1. Introduction

The most distinctive feature of estuaries is the variability caused by the mixing of saltwater from the ocean with freshwater from the land (Lucas et al., 2006; Valle-Levinson, 2010). Consequently, vertical mixing is the most important process affecting the dynamics of estuaries, as it determines the exchange flow, the stratification, the residence time, and/or the distribution of waterborne material (Geyer et al., 2008). On the other hand, estuarine stratification (ST) is related to the vertical variation in salinity and temperature, which inhibits vertical mixing (Jiang et al., 2009).

Estuaries can be classified as stratified, partially stratified/mixed or vertically mixed, depending on their vertical density structure (Pritchard, 1952; Cameron and Pritchard, 1963), which is directly related to the opposing forces generated by the buoyant nature of river discharges and the mixing potential of the tides. For instance, stratification could affect the mixing of wastewaters depending on the type of estuary or, at a local level, the type of stratification generated close to the discharge point. Moreover, such classification is highly correlated to external forces and their environmental variability since changes in estuaries occur on a continuum of spatial and time scales (Moyle et al., 2010).

The timescales of variability associated with potentially important estuarine processes range from seconds to decades (Jay and Smith, 1990a). Tidal forces dominate the short timescales of estuarine variability (hours to days) when freshwater flow is low, and winds contribute small amounts of variance. At intermediate timescales (days to fortnights), estuarine variability includes both tidal and freshwater flow, and wind effects. Over longer periods such as months, seasons, and years, the primary cause of estuarine variability is related with changes in the discharge of the major freshwater sources (Jay and Smith, 1990b; c; Chawla et al., 2008). In summary, it is likely that an estuary will describe an ellipse of variability of any parameter in consecutive tidal cycles from spring to neap tides, from month to month, dry to wet seasons, year to year, or from one location to another inside the same estuary (Valle-Levinson, 2010).

The evolution of estuarine stratification might be linked to the

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variation in water levels, velocities and densities (hydrodynamic key variables) by means of the classical Richardson's layer number (Ri_L) given by Bowden (1978) in equation (1).

$$Ri_L(t) = \frac{g \cdot H(t) \cdot \Delta\rho(t)}{\overline{\rho}(t) \cdot (\overline{u}(t))^2} \tag{1}$$

where g is gravity acceleration, $H(t)$ is the depth of the water column, $\Delta\rho(t)$ is the density at the bottom minus that at the surface, $\overline{\rho}(t)$ is the vertical mean-depth density, and $\overline{u}(t)$ is the vertical mean-depth velocity.

However, demonstrating such an evolution is still a hard task due to the complexity of the estuarine bathymetry, and the wide and continuous range of environmental variations (Roberts, 1999a; b), which complicate their analysis based on field data (Van Gastel and Pelegrí, 2004; Simpson et al., 2005; Geyer et al., 2008; Andutta et al., 2013; Pavel et al., 2013).

One way to tackle these issues is the use of the huge potential provided by numerical models (Moll and Radach, 2003). Numerical modelling avoids the use of field data only at discrete locations and allows the prediction of a continuous response (Severinsen et al., 1996; McIntyre and Wheater, 2004; Guérit et al., 2008). Indeed, they are convenient and useful tools to determine the spatial and temporal evolution of estuarine stratification during long-term periods (>30 years). In recent years, some advanced 3D numerical models have been developed for estuaries with an improved performance (Hervouet and Bates, 2000; Casulli and Zanolli, 2002; Lesser et al., 2004; Chen et al., 2003; Haidvogel et al., 2008). Unfortunately, this type of three-dimensional studies can be difficult to handle due to the generation of large results data sets, which require different techniques of data mining, (e.g. clustering and/or selection techniques), providing an easier analysis and description of the environmental variability (Camus et al., 2011; Bárcena et al., 2015).

Regarding hydrodynamic model scenarios, Bárcena et al. (2015) proposed a methodology to classify a reduced number of groups of river flow and astronomical tide in order to run numerical models with a considerable reduction in computational requirements. Such a methodology was applied to the Suances Estuary's case study, the results obtained highlighting the ability of K-means algorithm to classify long-term series (>30 years) of realistic hydrodynamic forcing with a reduced number of groups of short-term series (15 days). The proposed methodology allowed to explain the variability of any medium or long-term period, to select scenarios of realistic forcing series for running numerical models, and to reduce computational costs.

In this study, we focused on estuaries where the astronomical tide and river discharges are the most important forcing factor explaining the average behavior of estuarine hydrodynamics and, consequently, their stratification patterns. These types of estuaries are distributed worldwide, so a methodology to determine their stratification patterns could help researchers, technicians and/or policymakers to manage them more efficiently. Examples of these estuaries could be Suances (Bárcena et al., 2012a); Huelva (Sámano et al., 2012); Urdaibai (García et al., 2010); Mandovi (Vijith and Shetye, 2012); Mondego (Ascione Kenov et al., 2012); Hudson (Warner et al., 2005); Alafia (Chen, 2007); Tanshui (Liu et al., 2002); Columbia (Chawla et al., 2008); Yaquina (Frick et al., 2007); Ribble (Kashekipour et al., 2001); Haihe (Bai et al., 2003); or Humber (Edwards and Winn, 2006).

The objectives of this work were to develop a methodology and numerical tools to: a) define model scenarios of realistic forcing to run 3D numerical models, representative of all hydrodynamic conditions and based on K-means clustering; b) calculate the spatial and temporal evolution of estuarine stratification for each model scenario; and c) determine estuarine stratification patterns based on the forcing and the probability of occurrence of each stratification type.

2. Material and methods

2.1. 3D hydrodynamic model

Numerical modelling was conducted with the Delft3D-FLOW hydrodynamic model (Nicholson et al., 1997; Lesser et al., 2004). The Delft3D-FLOW consists of a numerical model based on finite differences that solves the unsteady shallow water equations in three dimensions (hydrostatic assumption). It aims to model flow phenomena when the horizontal length and timescales are significantly larger than the vertical ones (Lesser et al., 2004).

Delft3D-FLOW has been applied to numerous studies confirming its ability to simulate hydrodynamics in complex estuarine systems. For instance, Iglesias and Carballo (2010) implemented and applied it to understand how high winds affect the circulation of the Ría de Muros. García-Alba et al. (2014) applied it to determine the hydrodynamics of the Port of Marin (NW Spain), to couple them to a transport model (IH-Dredge) simulating the effects of dredging activities. Zhou et al. (2014) used this model to investigate the initiation and long-term evolution of tidal networks by comparing controlled laboratory experiments and their associated scaling laws with outputs from a numerical model. Finally, Jiménez et al. (2014) used it to scale properties of tidal networks from long-term numerical simulations in an ideal estuarine basin.

2.2. K-means clustering approach

Based on the K-means algorithm (KMA), Bárcena et al. (2015) developed a methodology to select short-time series (clusters) of realistic hydrodynamic forcing from a long-term time series, and to simulate the most probable scenarios occurring in estuaries driven by rivers and tides. The KMA computes a set of centroids, each of them characterizing a group of data such as a forcing time series, formed by the vectors in the database for which the corresponding centroid is the nearest one (more details in Hastie et al., 2001).

Since hydrodynamics respond nonlinearly to river and tidal forcing in an estuary, Bárcena et al. (2015) suggested the use of a simple formula which provides the values of a response dependent on both forcings, and embeds this nonlinear response. Accordingly, Bárcena et al. (2015) determined the minimum and optimal number of clusters needed to run numerical models using the water level predictand given by Bárcena et al. (2012a). This predictand was used as an indicator of the quality of the KMA classification.

2.3. Study area and available data

The Suances Estuary (−4.0237/43.4007 lat/lon ED50) is a mesotidal estuary located in the Spanish northern coast (Fig. 1). It is approximately 5.5 km long with a mean width of 150 m, and a surficial area of 389 ha, 76% of which are intertidal flats. Readers are referred to Bárcena et al. (2012a; b) and Bárcena et al. (2015) for further information about the Suances Estuary (SE).

Regarding field measurements, the authors collected information from two sources: (1) a field survey (CHN, 1998), and (2) the water quality monitoring network of the coast of Cantabria (IHCantabria, 2012). Fig. 1 shows the location of the sampling stations for both sources.

The field survey (CHN, 1998) took place during the last two weeks of January and the first week of February 1998. The field data included (see Fig. 1): 1) Measurements of tidal water levels at two points (TG1 and TG2), conducted every 5 min with a tidal pressure