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On the occurrence of tidal bores – The Garonne River case

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ABSTRACT

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In this paper we present the first intensive high temporal and spatial resolutions field investigation of tidal bore dynamics that was conducted during several months in the Garonne River (France). We show that, contrary to the common view, tidal bores are not limited to macrotidal environments and spring conditions. In the Garonne River, tidal bores form for a large majority of tides, with an occurrence percentage of 90% for low flow discharges and 65% for large flow discharges. A first field description of the subcritical/supercritical tidal bore transition is presented. We also bring to light the significant cross-section variability of undular bores in contrast to what is observed in existing rectangular channel experiments.

ADDITIONAL INDEX WORDS: *estuary, mascaret, undular bore, Froude number, breaking*

INTRODUCTION

A tidal bore is a positive surge propagating upstream that may form when a rising tide with significant amplitude enters shallow, gently sloping and narrowing rivers. Tidal bores have been widely observed worldwide in estuaries and rivers in regions with large tidal amplitudes (*e.g.* Tricker, 1965, Lynch, 1982, Simpson *et al*., 2004, Wolanski *et al*., 2004, Chanson, 2005). They have a significant impact on the river ecosystem behavior, especially in terms of sediment transport (Tessier and Terwindt, 1994, Chen *et al*., 1990).

Tidal bore propagation is a fascinating phenomenon which has been qualitatively observed in many places worldwide (Bartsch-Winkler and Lynch, 1988, Chanson, 2005). Most of the existing field studies were limited to visual observations. Only a few field experiments (*e.g.* Simpson *et al*., 2004, Wolanski et al., 2004, Uncles et al., 2006) have been devoted to a quantitative study of the tidal bore dynamics. Visual observations are limited to breaking bores or at least steep, large amplitude non-breaking undular bores, which occur for large tidal ranges and usually for small river discharges. These large amplitude tidal bores have specific names, such as *pororoca* in the Amazon River (Brazil) or *mascaret* in the Garonne and Dordogne rivers (France). The lack of quantitative field measurements and the predominance of qualitative visual observations of large amplitude tidal bores have lead to speculative conclusions about the tidal bore occurrence, which is commonly assumed to be limited to macrotidal environments and spring tide conditions (Chanson, 2005).

In the present paper we present an intensive field investigation of the tidal bore dynamics conducted during several months in the Garonne River, here for the first time with high temporal and spatial resolutions. We show that tidal bores form during a large majority of tides, even close to neap tides.

MATERIALS AND METHODS

Study area

The Gironde estuary is located in the Bay of Biscay, on the southwest coast of France and is formed from the meeting of the rivers Dordogne and Garonne (see Figure 1). The estuary shows a 75-km long regular funnel shape. In the Gironde mouth, the mean neap tidal range and mean spring tidal range is 2.5 m and 5 m, respectively. As the tide propagates upstream a marked ebb-flood asymmetry occurs in the upper reaches of the estuary and the wave is amplified (Castaing and Allen, 1981). This large-amplitude tidal wave propagates in the Garonne and Dordogne rivers up to 160 km from the estuary mouth (Bonneton *et al.*, 2011b). For example, on the 10th of September 2010 the tidal range was 5.1 m at the Gironde mouth, 6.1 m at Bordeaux and 6.3 m at Podensac. During spring tides and low fresh water discharge periods, large amplitude undular tidal bores (named *mascarets*) form in the two rivers (Parisot *et al*., 2010). In the Garonne River, *mascarets* occur between Bordeaux and Langon (point 3 in Figure 1). During the propagation, both the intensity and the shape of the bore are strongly dependent on the local river bathymetry. A bore may disappear in areas of deeper water and subsequently reform in shallow areas. A typical example, observed at the Podensac field site, is presented in Figure 2.

Field experiments

The field study was conducted in the Garonne River (France) at Podensac located 140 km upstream of the estuary mouth. This site was selected owing to the presence, during spring tide, of well-developed undular tidal bores (see Figure 2) and also because of the absence of any significant curvature of the river at this location, which limits the complexity of the tidal bore structure.

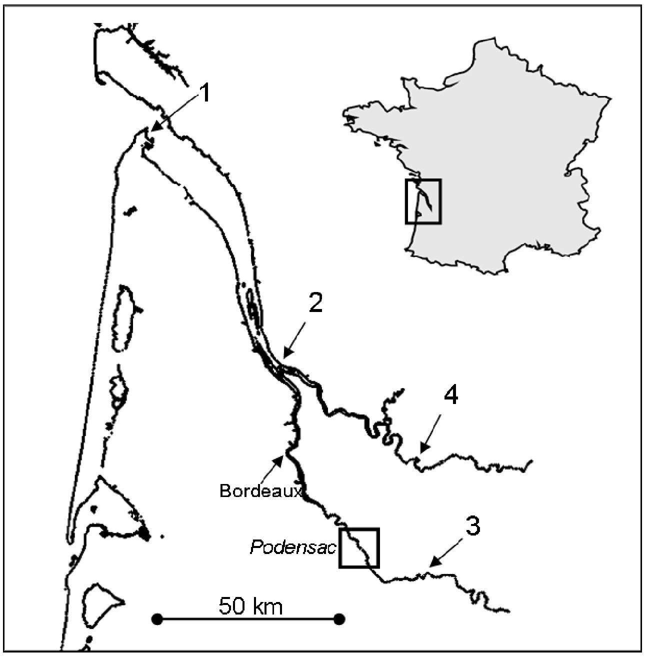

Figure 1. Location map of the Gironde estuary. Tide propagates in the estuary from Pointe de Grave (1) to Bec d'Ambes (2) and continues in the Garonne and Dordogne rivers. The limit of propagation of well-developed bore (*mascaret*) is marked by (3) and (4) on the Garonne River and the Dordogne River, respectively.

In order to observe tidal bores for a large range of tidal amplitudes, two field campaigns were conducted in 2010 around the spring and autumn equinox (see Figure 3). The first campaign, *Tidal Bore Garonne 1* (TBG1), took place between the 24th of February and the 15th of April, for large fresh water discharges (around 700 m^3/s) and the second one, TGB2, between the 1st of September and the 22nd of October, for low water discharges (around 125 m^3/s). A bathymetry survey of the 1-km long field site was done using a bottom-tracking ADCP (RDI).

During TBG1 campaign (see Parisot et al., 2010) instruments were moored along one section of the river. Two pressure sensors (Ocean Sensor System) sampled at 10 Hz were deployed in shallow water close to the two river banks. One Acoustic Doppler Current Profiler (ADCP-RDI) associated with a near-bottom Acoustic Doppler Velocimeter (ADV Nortek) were deployed in the deepest part of the 150-m river cross-section and continuously sampled at 2 Hz. For all the instruments, data were acquired during 17 tides from the 24th of February to the 5th of March 2010. In addition, one pressure sensor was deployed during 97 tides (see Figure 3a).

During the second campaign, TBG2, 17 instruments (6 pressure sensors (Ocean Sensor System), 3 ADCP (RDI), 1 AWAC and 2 ADV (Nortek), 2 Altimeters ALTUS (Ifremer/Micrel), 3 turbidimeters (OBS-3A/Campbell)) were set up along three sections of the river spaced at approximately 200 m intervals. For all the instruments data were acquired during 27 tides from the 1st to the 14th of September 2010 and for one pressure sensor during 99 tides (see Figure 3b). Pressure sensors were sampled at 10 Hz, ADV at 32 Hz and the others instruments at 2 Hz. The measurements were supplemented by intensive aerial and boat observations of the *mascaret* between Bordeaux and Podensac on the 10th of September. Two cameras were also installed on the field site to characterize the phase structure and celerity of the wave field associated with well-developed undular tidal bores (Bonneton *et al.*, 2011b).

The present paper focuses on tidal bore occurrence and mainly relies on water depth time series. Analysis of tidal bore velocity field will be presented in a companion paper (Bonneton *et al*. N., 2011). Two methods were used to measure high-frequency water depth time series. A classic one, based on pressure measurements, and a second one based on direct acoustic surface tracking measurements with the AWAC. Pressure measurements were converted to water depth, taking into account atmospheric pressure variations. Due to strong non-hydrostatic effects associated to well-developed tidal bores, a non-hydrostatic correction based on linear theory was applied to the data. This method has been validated by comparing its results with direct acoustic surface tracking measurements.

Flow conditions

The TBG1 campaign was conducted at the end of winter with large fresh water discharges, ranging from 650 to 750 m^3/s. On the opposite, the TGB2 campaign was carried out at the end of summer with low water discharges, ranging from 80 to 170 m^3/s. Both experiments spanned approximately 3.5 spring-neap cycles, including large amplitude equinox tides (see Figure 3). This corresponds to a survey of 97 tides for TGB1 and 99 for TGB2. The tidal range, $T_{R,}$ ranged from 2.5 m to 5.2 m for TGB1 (Figure 3a) and from 3.7 m to 6.5 m for TGB2 (Figure 3b). A significant low tide water elevation drop can be observed between TBG1 and TBG2, in agreement with the fresh water discharge evolution. A tidal anomaly (T_R = 5.7m), related to the *Xynthia*

Figure 2. Aerial photograph of the field site at Podensac (Garonne River) on the 10th of September 2010.

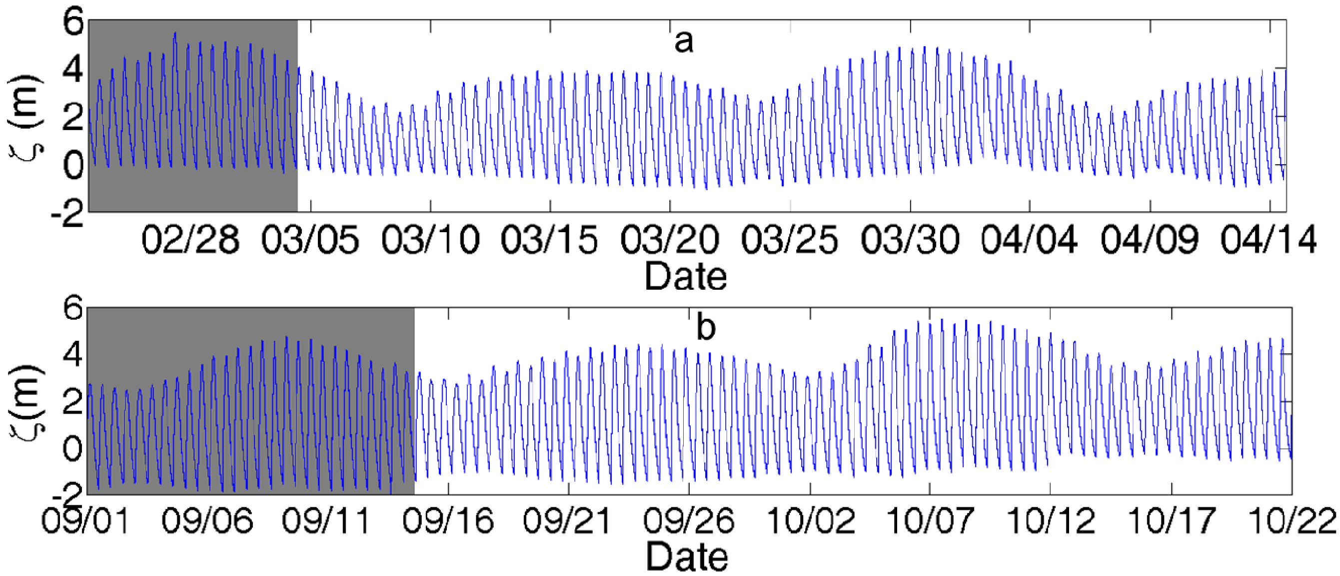

Figure 3. Time series of tide elevation (altimetry NGF-IGN69 system) at the field site during the two campaigns. The shaded areas indicate the intensive measurement periods. a, TBG1 campaign from the 24th of February to the 15th of April 2010; b, TBG2 campaign from the 1st of September to the 22nd of October 2010.

storm (in the night between the 27th and 28th of February) is readily apparent in Figure 3a.

RESULTS

During the TBG2 fieldwork, for large tidal ranges, low fresh water discharges contributed to the formation of well-developed undular tidal bores (Figure 2). It corresponds to one of the largest tide observed during the TBG2 campaign: T_R = 6.3 m. The three first wave fronts are non-breaking, excepted at the river banks. The next waves can locally break outside the river banks. Reflection of the first wave at the banks is clearly visible in Figure 2. This wave pattern is similar to those observed in trapezoidal channel by Treske (1994) for the same range of Froude number.

Time serie of local water depth concurrent to Figure 2 is shown in Figure 4a. The strongly asymmetric shape of the curve is characteristic of what we can observe at this location of the Garonne River, even for lower tidal range. A zoom (Figure 4b) on the moment where the tide flow turns to rising, confirms the presence a large amplitude tidal bore. This undular-type bore is associated with regular large amplitude secondary waves. The mean jump height is 0.9 m and the surge Froude number, based on cross-section mean water depth is 1.17. Comparisons between pressure measurements along a cross-section transect show that the mean jump is almost uniform across the river section. On the other hand, secondary waves are strongly variable across the river, in agreement with visual observations (*e.g.* Figure 2). The amplitude and the period of the first secondary wave measured in the deeper part of the river section are 0.53 m and 3.3 s, respectively. The height of the first wave front reaches 1.3 m. The bore celerity, measured with synchronized pressure sensors, is 5.4 cm/s which gives a secondary wavelength of 17.8 m, or divided by the cross-section mean water depth at low tide, a dimensionless wavelength of 4.8.

An analysis of the whole TBG2 data set (see Figure 3b) shows that tidal bores are not limited to large tidal ranges. During the 99 tides of the TBG2 campaign, tidal bores have an occurrence

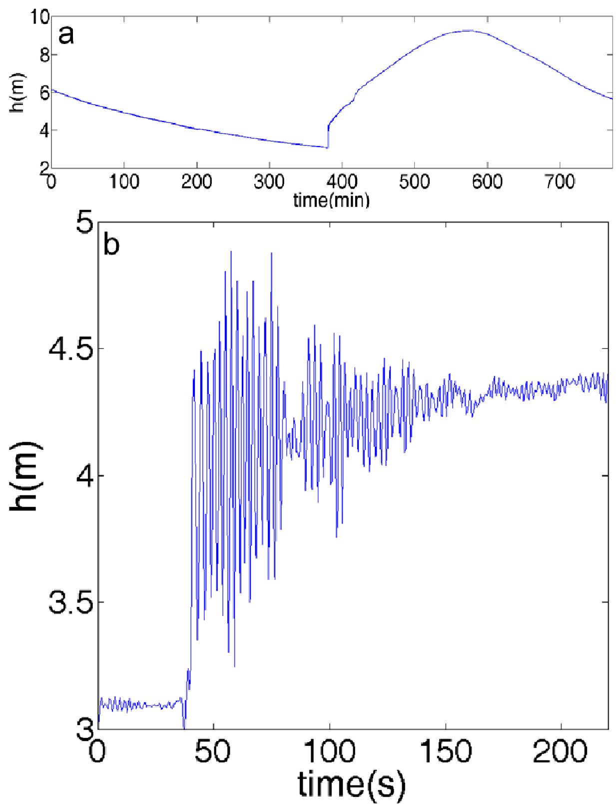

Figure 4. Water depth time series the 10th of September 2010, measured with the AWAC ADCP. Tidal range: T_R=6.3m. a, single tidal cycle; b, zoom at low tide.

percentage of about 90%. This observation challenges the common view that tidal bores are limited to spring tide conditions (Chanson, 2005).

The start of the flood of three consecutive increasing tides, close to the neap tide period, is presented in figure 5. If for T_R=4.15 m, surface elevation slowly increases (figure 5a), we observe undular bores for the next tides (figures 5b,c), which correspond to slightly larger tidal ranges: T_R=4.45 and T_R=4.65. The mean jump of these bores are small (22 and 27 cm) and the Froude numbers are equal to 1.04 and 1.05. For such low amplitude bores we observed a secondary wave with a period of 13.5 s, which is large in comparison with those observed for large amplitude tidal bores, i.e. *mascarets* (*e.g.* figure 4). It is worthwhile to note that, in contrast with *mascarets*, such low steepness bore cannot be visually observed. To our knowledge, this is the first time that such subcritical/supercritical tidal transition has been identified in the field. The bore celerity, measured with synchronized pressure sensors, is equal to 4.25 cm/s which gives a secondary wave wavelength of 57 m, or a dimensionless wavelength of 15. This dimensionless wavelength increasing with increasing Froude number is qualitatively in agreement with undular bore laboratory observations (*e.g.* Treske, 1994).

During the high-flow discharge TBG1 experiment (figure 3a), *mascarets* were not visually observable, but low steepness tidal bore were identified for 63 over 97 observed tides, which represents an occurrence percentage of 65%. This observation challenges the common view that tidal bores are limited to low-discharge conditions. One of the highest TBG1 bores, for a tidal range of 4.9 m, is shown in figure 6. We present comparisons between two synchronized pressure sensors moored along a river cross-section, in low tide water depths of 1.15 m (close to a river bank) and 5.70 m (deeper part of the cross-section). We observe that the 0.45 m mean jump is almost uniform across the river section. On the other hand, we note that the secondary wave amplitude is variable across the river, with higher amplitude close to the banks than in river centre. The height of the first wave front reaches 0.56 m in the river centre and 0.64 m close to the river bank. This result, for a Froude number of 1.06, is in qualitative agreement with trapezoidal channel experiments by Treske (1994).

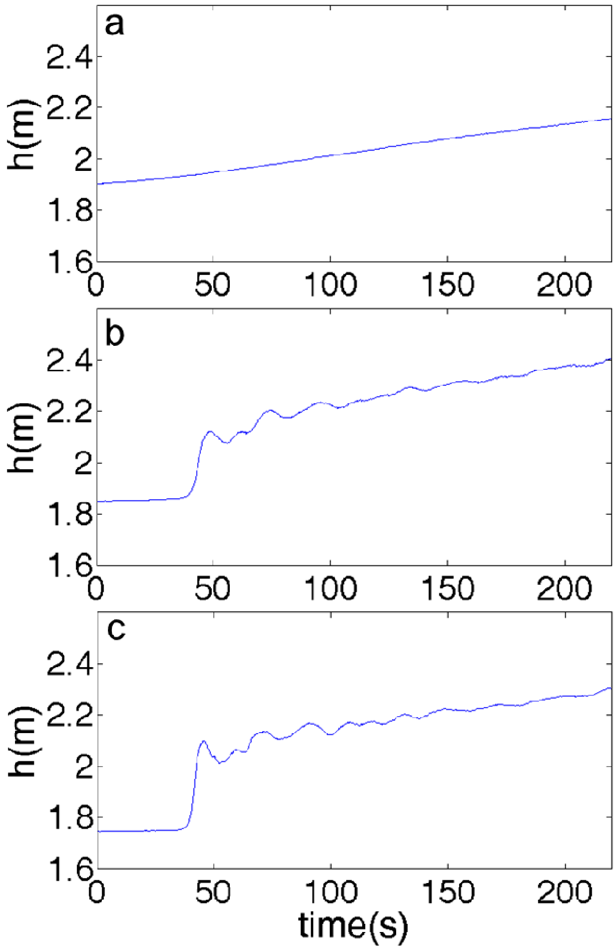

Figure 5. Water depth time series obtained from pressure measurements for three consecutive low amplitude tides during TBG2 campaign. a) 3 Sept. 22:37 TU, T_R=4.15 m; b) 4 Sept. 11:15 TU, T_R=4.45 m; c) 5 Sept. 00:19 TU, T_R=4.65 m.

CONCLUSION

This paper presents a first intensive field investigation of the tidal bore dynamics. We have shown that, contrary to the common view, tidal bores are not limited to macrotidal environments and spring conditions. In the Garonne River, tidal bores form for a large majority of tides, with an occurrence percentage of 90% for low flow discharges and 65% for large flow discharges. A first field description of the subcritical/supercritical tidal bore transition is presented. We have also brought to light the significant cross-section variability of undular bores that contrasts with rectangular channel experiments. This is in agreement with previous laboratory experiments performed by Treske (1994) with trapezoidal channels.

Data acquired during the two field experiments, TBG1 and TBG2, represent a unique database to improve our understanding of tidal bores. If the present study is essentially focused on bore occurrence, other investigations of this database are in progress, especially in terms of tidal bore induced boundary shear stress and sediment transport. These field results will also represent a unique opportunity to improve and validate fully nonlinear Boussinesq-type models (Bonneton *et al*., 2011a, Tissier *et al*., 2011), for the simulation of bore propagation for both tide and tsunami applications.

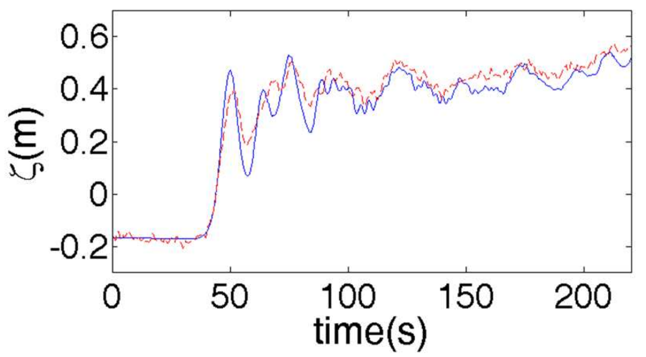

Figure 6. Water elevation time series (altimetry NGF-IGN69 system) the 4th of March (18:11 UT), when the tide flow turns to rising. Tidal range: T_R = 4.9 m. Comparisons between two pressure sensors along a river cross-section transect. Dashed line: elevation in the deeper part of the transect (5.70 m water depth à low tide); continuous line: elevation close to the river bank (1.15 m water depth at low tide).

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