

Wave-current interactions and infragravity waves at the Tagus Estuary mouth (Portugal)

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Abstract:

Estuary mouths subject to tides and waves generally exhibit complex hydrodynamics and sediment transport patterns where waves and currents interact, making the morphology of these coastal systems highly dynamic. Although they concentrate numerous socio-economic and environmental issues, their hydro-sedimentary dynamics remains only partly understood, in particular for the part exposed to ocean waves. This paper describes hydrodynamic measurements acquired over the Tagus Estuary mouth, one of the largest in Europe, during energetic winter conditions. The analysis of field data provides evidence for substantial tidal modulations of bulk wave parameters caused by water depth changes (*e.g.* wave energy dissipation by depth-induced breaking) and alternating currents (dissipation of high frequencies due to opposing currents during the ebb). In addition, measurements reveal interesting features with respect to infragravity waves, whose behaviour significantly varies between offshore (*i.e.* outside of breaking areas) and nearshore mooring stations. In particular, a substantial increase of their average period is highlighted during energetic conditions (up to 4-5 minutes) at a nearshore station located at the estuary entrance. According to recent findings conducted on a dissipative beach, a plausible explanation would be the merging of infragravity waves, due to the combination of free and bound waves across the several kilometre-wide surf zone. The development of such long period IG waves could provide an explanation for the frequent and intense coastal flooding events reported by inhabitants of a neighbourhood, Segundo Torrão, located at this specific site.

Keywords:

Wave-current interactions, Infragravity waves, Hydrodynamic measurements.

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1. Introduction

Due to their attractiveness, estuaries and their adjacent coasts concentrate many socio-economic and environmental issues such as erosion and coastal flooding risks, the management of sediment resources or the ecosystem preservation (*e.g.* water quality, nutrients, habitats). Estuaries exposed to the combined action of waves and tides exhibit complex hydrodynamics and highly-dynamic morphologic changes, whose governing processes are still not fully understood. Most studies on wave-current interactions were based on a modelling approach and concerned small to medium tidal inlet systems (*e.g.* BERTIN *et al.*, 2009; DODET *et al.*, 2013), and only a few were dedicated to larger mouth systems (*e.g.* RUSU *et al.*, 2011; ZIPPEL & THOMSON, 2017). In case of large estuary mouth, the literature on field observations remains scarce, in particular during energetic conditions due to difficulties in deploying and retrieving instruments. Furthermore, recent studies highlighted that infragravity waves (long waves due to the presence of groups in incident waves) could develop across wide surf zones during energetic conditions. Their relevance in the seasonal closure of wave-dominated tidal inlets has also been demonstrated (BERTIN *et al.*, 2019). This study aims at investigating nearshore wave propagation from field observations, including short and infragravity waves (hereafter SW and IGW, respectively), and their tidal modulations at the Tagus Estuary mouth during energetic conditions. This work is part of a citizen-science project (named *Nouveaux Commanditaires Sciences*; see Acknowledgments), whose research program has been set up following the request for a better understanding of the coastal erosion and marine flooding during storms. This request was expressed by severely affected inhabitants from an informal neighbourhood, Segundo Torrão (figure 1b; location PS_Torrao), who provide support for instrumental deployments and data acquisitions. The manuscript is organised as follows. The study site, field experiments and data analyses are presented in section 2. Results associated to field observations are presented and discussed in sections 3 and 4, respectively.

2. Field campaign and data analysis

2.1 Brief description of the study site

The Tagus Estuary, located on the west coast of Portugal, is one of the largest estuaries in Europe with a surface of around 320 km². The Atlantic Ocean connects to a shallow tide-dominated basin through a deep, long and 2 km-wide tidal inlet (figure 1). The continental shelf width is around 40 km in front of the mouth. The Tagus Estuary mouth is a semi-diurnal meso-tidal environment characterised by tidal ranges varying from 0.55 to more than 3.86 m at the coast (GUERREIRO *et al.*, 2015), and by a strong dominance of the ebb (FORTUNATO *et al.*, 1999). The wave regime is dominated by long-period swells generated in the North Atlantic Ocean. During the winter, offshore mean wave

conditions correspond to significant wave heights of 2.5 m, peak periods of 12.1 s and a mean wave direction of 305° (DODET *et al.*, 2010). Therefore, the Tagus Estuary is highly exposed to waves, which play a key role in its hydrodynamics, display strong interactions with currents (RUSU *et al.*, 2011), and can contribute to storm surges at the scale of the whole basin (FORTUNATO *et al.*, 2017). Lastly, complex bed morphologies are found at the mouth with an extensive ebb-delta shoal, the Bugio Bank (figure 1b), and with bed sediments mainly composed of medium sands (FREIRE *et al.*, 2007).

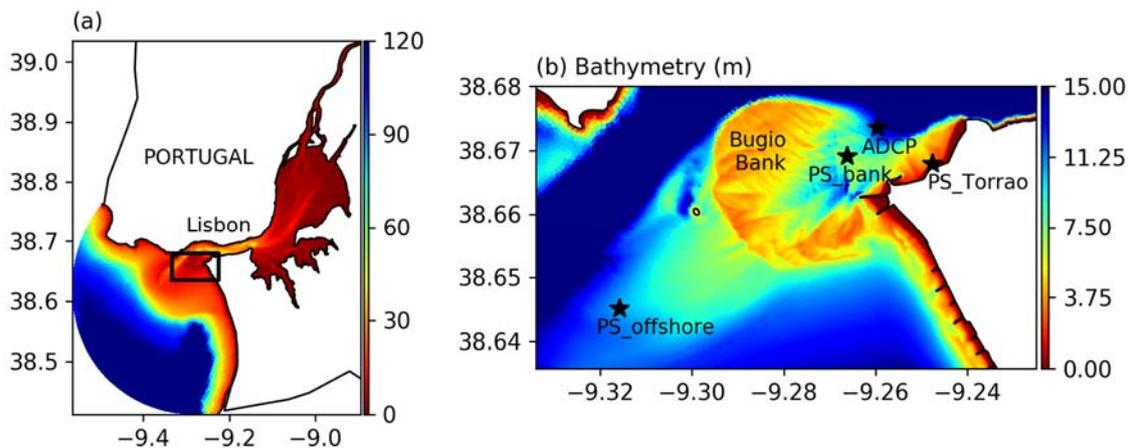


Figure 1. (a) Study site and its bathymetry (in m) with respect to mean sea level (2.26 m above chart datum) and (b) zoom on the Bugio Bank with locations of instruments indicated by black stars.

2.2 Field experiment

Three RBR pressure sensors and one 600 kHz ADCP (Acoustic Doppler Current Profiler) were deployed at the estuary mouth during one week (from the 16th to 24th November, 2019), during which an energetic event occurred with offshore wave heights (H_{m0}) and peak periods (T_p) reaching 6 m and 20 s (source: Portuguese Hydrographic Institute). From offshore to nearshore locations, sensors PS_offshore (-9.316; 38.645), PS_bank (-9.266; 38.67) and PS_Torrao (-9.247; 38.668) were respectively deployed at mean water depths of 10.6 m, 5.8 m and 2.8 m (figure 1b). PS_offshore and PS_bank were fixed to anchors directly deployed on the seabed whereas PS_Torrao was hooked up to a pillar, at 1.65 m above the seabed. Continuous pressure measurements were made at a sampling frequency of 2 Hz. The ADCP (-9.26; 38.673; mean water depth of 10.24 m), was set in an up looking configuration with 0.50 m-thick cells, providing average current profiles every 30 minutes and 20-minute bursts of pressure measurements every hour (at 2 Hz). Unfortunately, ADCP measurements are only available over the first 1.5 days of the field campaign, due to a malicious act.

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2.3 Data processing

To assess wave bulk parameters, pressure time series recorded at PS_offshore, PS_bank and PS_Torrao were split into 1 hour-long bursts, corrected from atmospheric pressure and detrended. Then, the free surface elevation was reconstructed using the Transfer Function Method based on linear wave theory (TFM; *e.g.* BISHOP & DONELAN, 1989) at PS_offshore, and the weakly dispersive nonlinear method described by BONNETON *et al.* (2018) at PS_bank and PS_Torrao, which enables to derive elevation of nonlinear waves propagating in shallow water. To exclude the noisy part of the signal, the reconstruction methods require the definition of an upper cut-off frequency, f_{max} , which was fixed at 0.3 Hz for all pressure sensors. The elevation variance spectra $E(f)$ associated to frequencies f were computed by applying a Fast Fourier Transform and by considering 10 Hanning-windowed segments (with an overlap of 50%), leading to a frequency resolution of 0.003 Hz. From each spectrum, wave parameters can be computed using the p -th moments, m_p , that correspond to the integration of $f^p.E(f).df$ between two cut-off frequencies, f_{min} and f_{max} . Thus, significant wave height H_{m0} can be computed as $4 \times (m_0)^{0.5}$ and the mean wave period T_{m02} as $(m_0/m_2)^{0.5}$. According to ROELVINK & STIVE (1989), an adaptive f_{min} value was defined as half of the continuous peak frequency, $f_{pc}=(m_0)^2/(m_2.m_1)$, firstly derived between 0.04 and 0.4 Hz (*i.e.* in the gravity band). Such an adaptive lower cut-off frequency, hereinafter $f_{min,SW}$, enables a more accurate distinction between infragravity and gravity bands of spectra, according to the maximum energy frequency. Finally, wave parameters associated to SW, $H_{m0,SW}$ and $T_{m02,SW}$, are derived by integrating spectra between $f_{min,SW}$ and f_{max} , while those associated to IGW, $H_{m0,IGW}$ and $T_{m02,IGW}$, are integrated until $f_{min,SW}$.

3. Results

3.1 Short waves

Temporal evolution of SW parameters $H_{m0,SW}$, $T_{m02,SW}$ and T_p (figure 2b,c,d) highlight that the deployment period is characterised by calm conditions at the beginning, followed by an energetic period with $H_{m0,SW}$ values reaching almost 4 m at PS_offshore. At this location, the tidal modulation of mean wave parameters substantially differs with the one observed at other locations. While no significant modulation is observed for $H_{m0,SW} < 1$ m, a pronounced increase in $H_{m0,SW}$ is highlighted at low tide for moderate to energetic conditions. In particular, the three low tides starting from the 20th of November are characterized by very strong $H_{m0,SW}$ increases, reaching up to 1 m compared to the high tide situation (*i.e.* between +30% and +50%). It is interpreted that low water levels promote wave refraction over the western part of the Bugio Bank. Over the whole period, $H_{m0,SW}$ at low tide are on average 16% higher than during high tide at PS_offshore. Note that $T_{m02,SW}$ exhibits a marked tidal modulation during the most energetic period, with an increase during the flood and a decrease during the ebb (+/- 2 s).

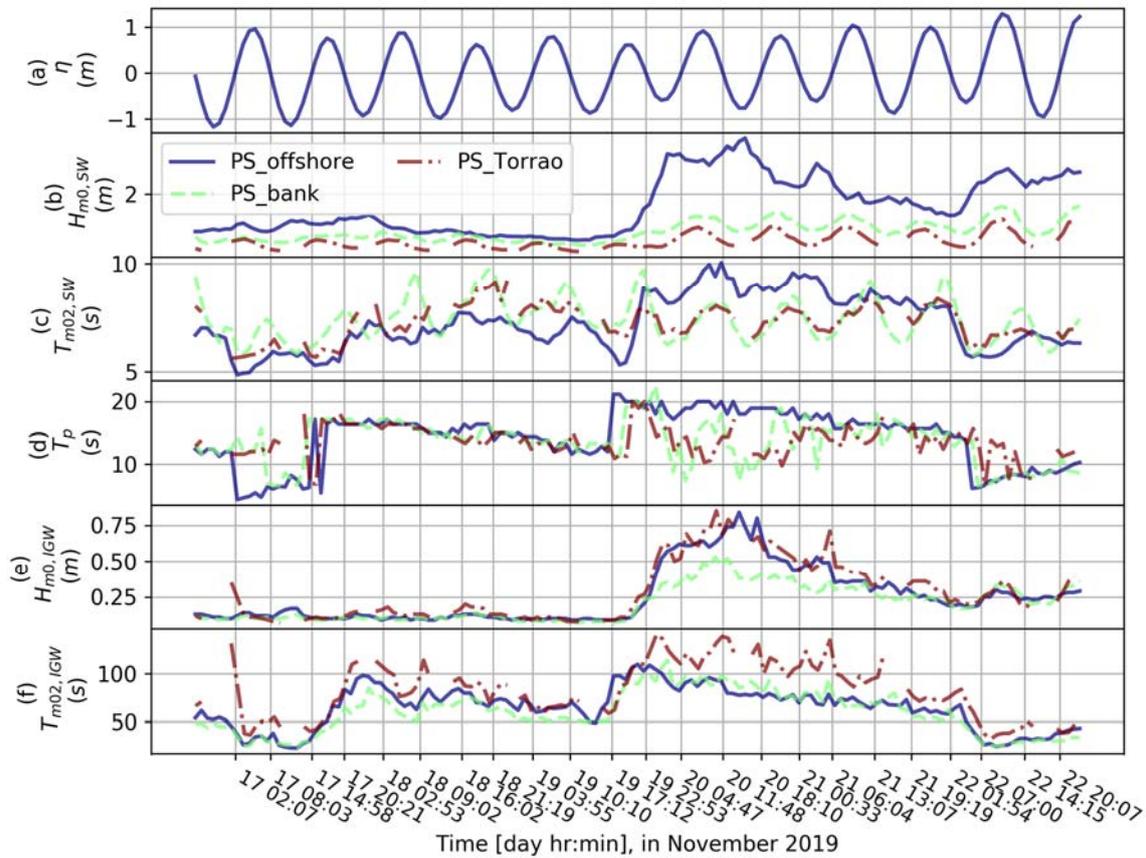


Figure 2. Temporal series of waves parameters associated to short waves ($H_{m0,SW}$, $T_{m02,SW}$, T_p) and infragravity waves ($H_{m0,IGW}$, $T_{m02,IGW}$), measured at the different stations. Water elevations around the mean sea level η on (a) are taken at PS_offshore.

At PS_bank, located at the NE part of the Bugio Bank, a very strong tidal modulation is observed. First, $H_{m0,SW}$ and $T_{m02,SW}$ at high tide are 48% and 18% higher than during the low tide, respectively (figures 3a and 3b). This behaviour is explained by more intense wave energy dissipation due to depth-limited breaking over the Bugio Bank at low tide. Moreover, substantial differences can be underlined between the flood and the ebb, by considering similar water depths. During the flood, $H_{m0,SW}$ are on average 19% higher whereas $T_{m02,SW}$ and T_p are respectively 20% and 15% lower (see $H_{m0,SW}$ and $T_{m02,SW}$ correlations on figures 3c and 3d). This can be attributed to current effects on the wave field propagation. Indeed, the presence of a tidal secondary channel on figure 1 suggests strong tidal currents over this region, as those measured at the ADCP location. ADCP data (not shown) reveal pronounced currents, oriented SW-NE, with velocities around 0.7 m/s during the flood and reaching up to 1 m/s during the ebb.

Similar conclusions can be drawn at PS_Torrao, located more inside of the estuary, where waves are expected to have experienced more transformation and dissipation. On the one

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hand, $H_{m0,SW}$ and $T_{m02,SW}$ at high tide are on average 2.5 times and 12% higher than during low tide. On the other hand, at mid-flood, $H_{m0,SW}$ are on average 88% higher than at mid-ebb, whereas wave periods are generally 15 to 20% lower. Indeed, a marked reduction of the wave energy associated to high frequencies ($f > 0.2$ Hz) is observed during the ebb, that is, when strong currents oppose wave propagation. Thus, it is interpreted that opposing currents make very short waves break by increasing their steepness, which reduces $H_{m0,SW}$ but increases the average period $T_{m02,SW}$.

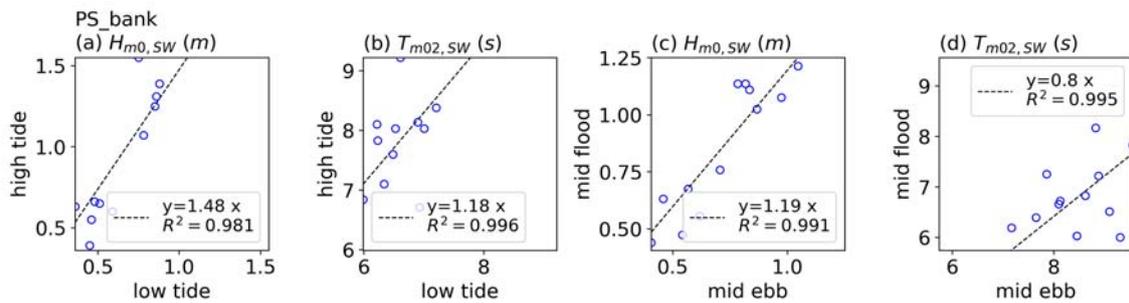


Figure 3. Correlations between SW bulk parameters ($H_{m0,SW}$ or $T_{m02,SW}$) observed during successive high and low tides, or mid-flood and mid-ebb phases (circles) at PS_bank.

Dotted lines depict linear regressions and R^2 refers to determination coefficients.

3.2 Infragravity waves

At PS_offshore, IGW are weakly influenced by water depth and current variations caused by tides (figure 2e,f). Indeed, this sensor is probably located outside of areas subject to wave breaking or intense circulations. $H_{m0,IGW}$ are lower than 0.2 m during calm periods and vary between 0.5 and 0.85 m during more energetic conditions. Their mean periods mainly vary from 50 to 100 s.

A decrease of $H_{m0,IGW}$ is observed from PS_offshore to PS_bank. It may mean that, on the one hand, IGW experience many transformations over the Bugio Bank, and on the other hand, that these two stations are not perfectly aligned with the mean wave direction. At PS_bank, $H_{m0,IGW}$ and $T_{m02,IGW}$ are relatively similar between mid-flood and mid-ebb, considering similar water depths. This indicates that, unlike SW, their propagation does not seem to be influenced by tidal currents. However, they appear to be more affected by water depth changes. $H_{m0,IGW}$ at high tide are on average 17% higher than during the low tide situation. This behaviour agrees with previous remarks suggesting a dependency of IGW to transformations experienced by SW groups over the Bugio Bank (evoked to explain differences between PS_offshore and PS_bank).

At PS_Torrao, $H_{m0,IGW}$ are generally higher than at PS_offshore (+16% on average). Compared to the offshore site, substantial increases in $T_{m02,IGW}$ values are observed throughout the period (+30% on average; figure 2f), in particular during energetic conditions (up to +90%). Regarding the tidal modulation, for similar water depths, $H_{m0,IGW}$ (resp. $T_{m02,IGW}$) is on average 10% higher (resp. lower) during mid-flood

compared to the mid-ebb situation, that may be due to SW transformations or refraction by tidal currents. At high tide, $H_{m0,IGW}$ (resp. $T_{m02,IGW}$) is on average 15% higher (resp. lower) than during low tide. Dealing with IGW, one of the most noteworthy results holds in the strong increase of $T_{m02,IGW}$ highlighted at PS_Torrao during the energetic period in comparison with observations at other stations (figure 2f; between the 19th at 11pm and the 21st at 6am). Focusing on the peak of the energetic period (20th November at 2pm), figure 4 provides evidence for long-period IGW (period reaching 4-5 minutes) at PS_Torrao, not observed at the offshore site. Note that, due to its location, the incoming wave energy is frequently dominant in the infragravity band during energetic conditions. Actually, the pressure sensor at Segundo Torrão was deployed over a two-month period (from the 25th October to the 27th December 2019), including several major storms such as *Fabien* (22nd December), during which $H_{m0,IGW}$ associated to IGW appeared to be dominant over SW, and reached up to 1.5 m. The mechanism expected to contribute to the development of these long-period IGW during energetic conditions is discussed in section 4.

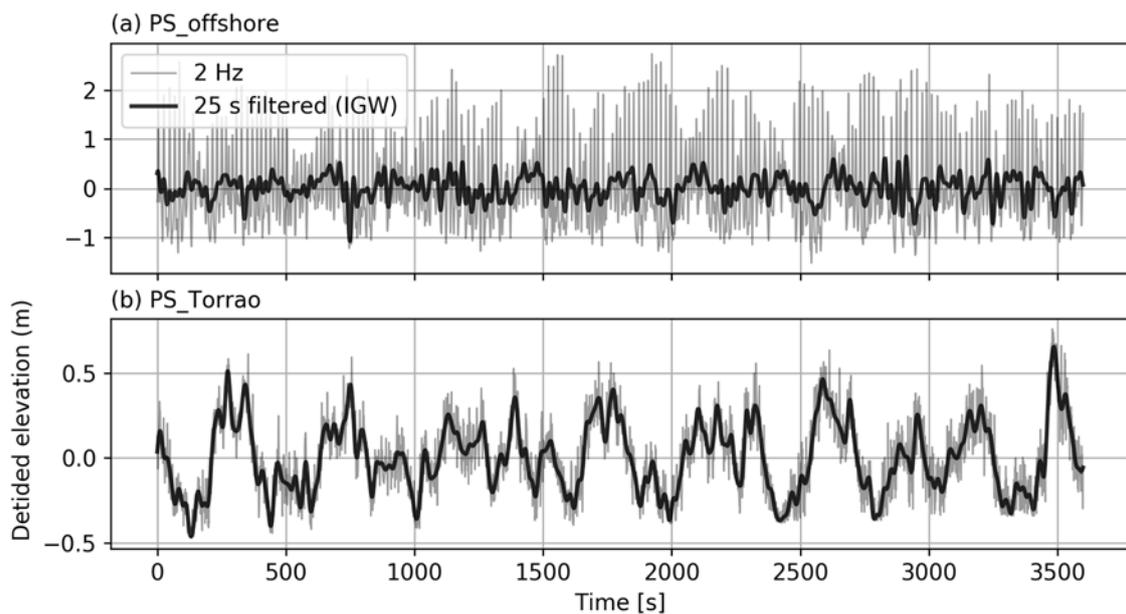


Figure 4. Detided elevations obtained at the peak of the energetic period (1-hour series starting from the 20th November at 2 pm) at PS_offshore (a) and PS_Torrao (b). Thick black lines refer to infragravity waves, obtained by filtering all periods lower than 25 s.

4. Discussion and concluding remarks

New field observations collected at the mouth of the Tagus Estuary under storm waves highlight a substantial tidal modulation of short waves bulk parameters, including first dissipation induced by depth-limited breaking over the Bugio Ebb-delta depending on water levels, in agreement with previous findings reported on wave-current interactions

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at the mouth of tidal inlets (*e.g.* OLABARRIETA *et al.*, 2011). In addition, present results reveal that the combination of dissipation due to depth-limited breaking and strong opposing currents during the ebb induces a sharp reduction of the wave energy in the high frequency part of the wave spectrum, which results in a marked decrease (*resp.* increase) of wave heights (*resp.* periods) compared to the flood phase. Indeed, intense currents oriented SW-NE and reaching up to 1 m/s have been measured at the estuary mouth (ADCP location), in agreement with hydrodynamic circulations reported in the literature (FORTUNATO *et al.*, 1997). Under strong opposing currents, it is generally mentioned that the wave energy propagation can be partly or completely blocked (*e.g.* OLABARRIETA *et al.*, 2011; ARDHUIN *et al.*, 2012). Ebb currents are commonly identified to promote wave steepness and enhance wave breaking. During energetic conditions, low water levels probably promote wave refraction over the western part of the Bugio Bank (PS_offshore), which leads to an increase of short wave heights up to 1 m at low tide. This indicates some significant variations of the wave breaking point and consequently of the surf zone width depending on tidal oscillations. Thus, substantial modulations of short waves properties by tidal-induced water depth and current variations have been highlighted over the Tagus Estuary mouth.

Regarding infragravity waves, according to BERTIN *et al.* (2020), the development of several kilometric-wide surf zones could promote the formation of long-period infragravity waves through the merging of bound and free waves. Infragravity waves measured at Segundo Torrão with periods of 4 to 5 minutes may result from similar processes and could explain coastal flooding events reported by local populations during storms. Indeed, the formation of long-period IGW (strong increase of $T_{m02,IGW}$ towards the coast) occurs during energetic incident wave conditions, which results in the development of a very large surf zone over the Bugio Bank, maximum in the alignment of Segundo Torrão. To our knowledge, such long-period infragravity waves have never been observed at the scale of a wide estuary like the Tagus during energetic conditions. This suggests that infragravity waves can be a relevant process influencing the hydrodynamics of wave-exposed estuaries.

To go further regarding the implications of wave-current interactions and infragravity waves on the overall hydro-sedimentary dynamics, numerical simulations will be performed using a 3D model based on the full coupling between circulation, waves and sediment transport. Indeed, fully coupled modelling systems were shown to be powerful tools to investigate physical processes as those discussed in this study (*e.g.* OLABARRIETA *et al.*, 2011; DODET *et al.*, 2013). For instance, the effect of tidal currents can be switched off in the wave model. These future researches will aim at improving our understanding of physical processes controlling the Tagus Estuary hydrodynamics, and their consequences on sediment transport and morphodynamics, since both wave-current interactions and infragravity waves have already been identified

as major contributors of sediment dynamics over small tidal inlets (DODET *et al.*, 2013; BERTIN *et al.*, 2019).

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