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Infragravity currents in a small ría: Estuary-amplified coastal edge waves?

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ABSTRACT

Observations are presented of estuarine infragravity oscillations in a very small estuary, the Ría de Santiuste, northern Spain, that discharges into a bay. Time-scale calculations and measurements indicate that the most likely source of amplified infragravity waves within the estuary are coastal edge waves, which appear to be resonating between the headlands of the bay, and onshore-offshore seiching of waters that may be resonating between the beach and the bay's seaward limit. Infragravity waves in the estuary have a narrow, power-dominant periodicity range of 4.3–4.8 min. Generally, only very weak waves, and at other periodicities, occur within the tidal river when it is unaffected by the tide. Although infragravity water-level amplitudes are small in the tidal river, typically ~0.01 m during high water, the corresponding velocity amplitudes are significant, typically ~0.1 m s^{-1}, despite the occurrence of high runoff conditions during these measurements. Within the estuary and close to the mouth, near-bed salinity shows considerable variability that is a consequence of salt wedge oscillations with periodicities that are within the range of 4.3–4.8 min. Model results for simulated neap to spring high-water water levels show that wave periodicities in the range 3.5–4.5 min correspond approximately to $3\lambda/4$ resonances. The model also indicates that an effect of low runoff is to greatly enhance resonant behaviour within the estuary, such that water level amplitudes of 0.02 m at the mouth can produce wave currents as fast as 0.4 m s^{-1} within the estuary, compared with ~0.1 m s^{-1} during high runoff.

1. Introduction

Infragravity waves are usually considered to be long-period oscillations with periodicities in the range 20 s (sometimes stated as 25 or 30 s, e.g. Munk, 1950; Reniers et al., 2010; López and Iglesias, 2013) to several minutes (Masselink and Hughes, 2003), which overlap and exceed those of wind-generated gravity waves (0.3–30 s), although they may ultimately derive their energy from these waves or directly from the wind (Munk, 1950; Masselink and Hughes, 2003; Aagaard and Hughes, 2013; de Bakker et al., 2014). Small estuaries and harbours generally are protected from the effects of ocean surface gravity waves, but are nevertheless susceptible to the effects of longer period infragravity waves. Whereas water level fluctuations may be small, the velocities associated with infragravity waves can lead to significant water movements and, e.g., to mooring ropes parting on commercial vessels when tied alongside in the harbours of large, commercially important estuaries (Jackson, 1980; López, 2012; Wang et al., 2013), and to similar disruptions for small leisure and fishing craft in smaller estuaries and other harbours (Okihiro and Guza, 1996). The study of these motions is therefore of applied as well as research interest, especially if there is the possibility of resonant amplification within an estuary and its harbours (Sobey, 2003; Chen et al., 2004; Dong et al., 2013). This article is concerned with observations of infragravity oscillations and their propagation from coastal zone to upper estuary.

Although it has been known for many years that periodic water level oscillations in coastal areas can cause seiching and may lead to resonance within neighbouring bays, estuaries and harbours, the topic remains of great interest and continues to be studied in the context of a variety of coastal systems (e.g. the northern Maltese Islands, Drago, 2008; Monterey Bay, US, Breaker et al., 2010; Elkhorn Slough, an estuary directly connected to Monterey Bay, Breaker et al., 2008; Eprapah Creek, Australia, Trevethan et al., 2007; Port Ferrol, Spain, López et al., 2012; Hualien Harbour, Tawain, Chen et al., 2004). This interest has led to the development of various modelling methodologies for the determination of infragravity wave properties (e.g. Battjes, 2006; Reniers et al., 2010;

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Wang et al., 2011; Dong et al., 2013; López et al., 2013; Wang et al., 2013; Rijnsdorp et al., 2014), partly because an ability to predict the consequences of such long waves in a harbour is important for the management of ports.

Infragravity waves also affect coral reefs (Sheremet et al., 2011; Van Dongeren et al., 2013), influence beach and coastline morphology (Battjes, 2006), sometimes dominate residual sediment transport within the surf zone (Aagaard and Greenwood, 2008) and the near-shore, causing both preferred directions of sediment transport (e.g. Roelvink and Stive, 1989; Dehouck et al., 2009) and significant sediment suspension variability on time-scales of 20–100 s (Aagaard and Hughes, 2013). Infragravity waves also can cause wave run-up and overtopping on dunes and dikes (van Gent, 2001), over-wash and dune erosion (van Thiel de Vries et al., 2008; Roelvink et al., 2009).

Infragravity wave generation is related to several factors, including forcing either directly or indirectly by groups of surface gravity waves (Aagaard and Hughes, 2013). Measurements at Port Ferrol (López et al., 2012) and from several locations in a gently sloping beach multiple-bar system (Sheremet et al., 2002), showed that temporal variations in infragravity wave energy were strongly related to onshore incident wave energy, suggesting a non-linear energy transfer from $<$20 s sea and swell waves (de Bakker et al., 2014), and that infragravity wave energy was more strongly correlated with swell-wave rather than sea-wave energy; infragravity energy also varied with tidal water level.

Infragravity-wave seiching and resonance within estuaries has received less attention than that within ports and harbours. Generally, research in estuaries has focused on much longer-period resonances, such as the 2 day resonant periodicity of Chesapeake Bay (Zhong et al., 2008) and the semi-diurnal tidal resonance of the Bristol Channel system, UK (e.g. Zhou et al., 2014), the Bay of Fundy, Canada (Garrett, 1972), Long Island Sound, US (Wong, 1990), the Gulf of Saint Vincent, Australia (Bowers and Lennon, 1990) and, although wind-driven, the Albemarle–Pamlico Estuarine System, US (Luettich, 2002). Modifications to an estuary that bring it closer to tidal resonance can have profound effects on its sediment transport properties and turbidity (Schuttelaars et al., 2013; de Jonge et al., 2014). At shorter periodicities, the sixth-diurnal tide appears to resonate in the estuarine part of the Firth of Forth, Scotland (Elliot and Clarke, 1998) and, at even shorter periodicities, Bowers et al. (2013) describe a seiche of periodicity roughly 2.5 h that occurs around high water (HW) in the coastal waters of the long, narrow, Menai Straits, Wales. Trevethan et al. (2007) describe long-period oscillations of the longitudinal velocity in an estuarine creek, with a period of approx. 1 h, which were believed to result from resonance between the creek and its outer bay system; also observed were some flow reversals that occurred around high water and the early ebb, with periods between 11 and 14 min, which were thought to be due to resonant behaviour, and Breaker et al. (2008) measured wave periodicities of 22 min and longer in Elkhorn Slough.

The overall objective of this paper is to present information on the behaviour of long-period, infragravity waves within the estuarine environment in order to enhance our understanding of the processes at work and to add to the (currently very limited) published data that appears to be available for the study of these processes in the estuarine environment. Individual aims are: (a), demonstrate the existence of infragravity waves in the coastal zone near the mouth of the estuary and measure their associated currents and water levels; (b), demonstrate the propagation of coastal infragravity waves into the lower estuary, including their periodic forcing of salt-wedge movements, their progression into the upper estuary, and their amplification *via* resonance within the estuary; (c), develop and utilise a barotropic, hydrodynamic model to determine resonant frequencies within the estuary and demonstrate that the estuary is close to $3\lambda/4$ resonance for the observed, amplified infragravity waves, and; (d), utilise theoretical estimates for resonance and seiching time-scales in the coastal zone and estuary to evaluate potential driving mechanisms for the infragravity waves. Of these aims, item (b) provides new insights into the interactions between an estuary and infragravity waves. The 'relevance' of these interactions is clear for a commercial port that is located within an estuary, but in general will depend on the particular estuary or creek of interest; nevertheless, the potentially fast and relatively rapidly changing currents generated by infragravity waves may cause alarm and be hazardous to estuarine users and impact both on morphology and man-made structures, such as training walls and pontoons, as well as influence the sedimentary and ecological environment.

2. The estuary and its environment

The Ría de Santiuste is a very small, canalized estuary in the Principality of Asturias, northern Spain (Fig. 1a,b). It is the estuary of the Río Cabra and typically is about 20 m wide at HW. The estuarine topography is defined by its river, the cliff and hard-shore west bank, and the training wall and road wall that have been built between the eastern bank of the river from the road bridge (Fig. 1b) to just beyond the HW line on the sandy beach of Playa de la Franca, a distance of approximately 500 m (Fig. 1c); thereafter it becomes an untrained, eroded channel in the beach that is exposed at low water (LW). There is a deepening of the channel just inside the training wall mouth, followed by a rapid rise in bed level to a relatively horizontal channel (Fig. 1c). Approximately 500 m from the mouth, in the vicinity of the Road Bridge, there is a further rapid rise in bed level.

The Río Cabra is a short (roughly 10 km long) river that has its freshwater source issuing from a cave in a karst area of the Sierra de Cuera that lies between the Bay of Biscay and the Picos de Europa mountain range of Asturias. It is estimated that runoff was approximately 7 $m^3\ s^{-1}$ on average during the 2004 survey, following high rainfall. It is much lower during low rainfall summer months.

At LW the estuary becomes an extension of the Río Cabra that flows into the sea after leaving the mouth and crossing the beach. At rising mid-tide the saltwater enters the trained part of the ría and moves up-estuary as a salt wedge, reaching approximately the Road Bridge at spring tides. At higher river runoff (approximately 9 $m^3\ s^{-1}$ in the case illustrated) the salt-wedge extends only 150 m into the estuary (Fig. 1c). Tides at La Franca are semidiurnal, with mean spring and neap tidal ranges of approximately 3.6 and 1.4 m, respectively, and a mean range of 2.5 m (Admiralty Tide Tables, 2003).

3. Methods

3.1. Deployments and longitudinal survey

A field campaign was undertaken during 9–11 April 2004 in conditions of heavy rainfall and high freshwater runoff. These conditions restricted instrument deployments, turned most of this small estuary into a tidal river and, with hindsight, reduced the effects of coastal long-period waves on the estuary. Tides decreased from mean springs to large neaps (approximately mean tides) during the survey.

Two bottom-mounted rigs were deployed on 9 April 2004, one at each of two stations. A multi-parameter instrument was moored at a third station and another was used for profiling during a longitudinal survey of the estuary. Each bottom-mounted rig