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Observations of nearshore infragravity wave dynamics under high energy swell and wind-wave conditions

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ABSTRACT

Infragravity waves (0.005–0.04 Hz) can dominate the water motion close to shore on low sloping beaches and play a significant role in beach and dune erosion. A new field data set of water surface elevation at 15 cross-shore locations on a dissipative, fetch-unlimited beach is analysed to investigate the forcing and surf zone behaviour of infragravity waves during a wide range of offshore wave conditions (H_o=0.38–3.88 m; T_p=6–20 s). Infragravity waves approach the shore as bound waves lagging slightly (~4 s) behind the short wave (0.04–0.33 Hz) envelope and are released in the surf zone as free waves. Infragravity wave heights of up to 1 m are measured close to shore and are best predicted using an offshore forcing parameter that represents the short wave energy flux ($H_o^2T_p$). Considerable infragravity dissipation is observed in the surf zone and dissipation increases with offshore wave energy. Dissipation is highly frequency-dependant and a frequency-domain Complex Empirical Orthogonal Function analysis reveals (quasi-)standing waves at frequencies < 0.017 Hz, but an increasingly progressive wave pattern at higher frequencies with reflection coefficients < 0.1, indicative of more than 90% dissipation. Much of the observed dissipation occurs very close to shore and the dependence of the reflection coefficient on a normalised bed slope parameter implies that energy at high infragravity frequencies is dissipated by wave breaking, since these frequencies fit into a mild sloping regime. This is supported by the results of bispectral analysis which show predominantly infragravity-infragravity interactions in shallow water and the development of infragravity harmonics indicative of steepening and eventual breaking of the infragravity waves.

1. Introduction

Infragravity waves, or long waves, are low frequency waves (typically 0.005–0.05 Hz) that make up a significant proportion of the total energy in the inner surf zone. Unlike sea-swell waves, which break and become saturated in the surf zone (Thornton and Guza, 1982), infragravity wave height has been observed to increase shoreward from up to a few cm in deep water (e.g., Aucan and Ardhuin, 2013; Crawford et al., 2015) to over 1 m close to shore (e.g., Guza and Thornton, 1982; Ruessink et al., 1998; Senechal et al., 2011; Fiedler et al., 2015). As a result, infragravity waves play an important role in beach and dune erosion (e.g., Russell, 1993; de Vries et al., 2008; Roelvink et al., 2009). Infragravity wave height in the nearshore, or at the shoreline as runup, has frequently been shown to be positively correlated with offshore wave height (e.g., Guza and Thornton, 1982; Ruessink et al., 1998; Ruggiero et al., 2004; De Bakker et al., 2014). However, the relationship between offshore wave period and infragravity waves, particularly their behaviour in the surf zone, has received less attention.

A stronger correlation between nearshore infragravity energy and offshore energy in the swell frequency band (0.04–0.14 Hz) than that in the sea frequency band (0.14–0.33 Hz) was observed by Elgar et al. (1992) and Ruessink (1998). The findings of Stockdon et al. (2006) indicate that a parameter accounting for both offshore wave height and wave period is crucial in explaining the variability in infragravity runup and observe a strong relationship with $(H_oL_o)^{1/2}$, where H_o is offshore wave height and L_o is the deep water wavelength. These findings were validated by Senechal et al. (2011) who found that infragravity wave runup during extreme storm conditions has considerably less scatter when correlated with $(H_oL_o)^{1/2}$ than with H_o only. Contardo and Symonds (2013) report a 30% stronger infragravity wave height response to long period incident swell than to short period wind-sea during low-moderate forcing conditions. Furthermore, Ardhuin et al. (2014) found the infragravity wave height in deep water to be strongly correlated with a parameter that includes both wave height and mean wave period and also found the largest infragravity wave heights to

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correspond with the largest mean period rather than the largest sea-swell wave height.

Two main mechanisms exist for the generation of infragravity waves. Biésel (1952), followed by Longuet-Higgins and Stewart (1962) and Hasselmann (1962), demonstrated theoretically that infragravity waves can originate well seaward of the surf zone by difference interactions between pairs of waves at sea-swell frequencies. This excites a group-bound, second-order wave with the same wavelength and period as the wave group, but is 180° out of phase. In the surf zone, where the short wave height becomes depth-limited and wave groupiness is significantly reduced, bound infragravity waves may be released to propagate shoreward as free waves (e.g., Masselink, 1995). However, Baldock (2012) argues, based on Longuet-Higgins and Stewart (1962), that bound infragravity waves will be progressively released when the short waves are in shallow water and the bound wave satisfies the free wave dispersion relationship, which can occur seaward or shoreward of the short wave breakpoint. An alternative generation mechanism, proposed by Symonds et al. (1982), is the time-varying breakpoint theory in which infragravity waves arise from oscillations in wave set-up/down as a result of the fluctuating breakpoint of different size wave groups. These breakpoint forced long waves have the same frequency as the wave groups and radiate away from the breakpoint in both the shoreward and seaward direction. The dominant generation mechanism is likely to depend on beach slope (Battjes et al., 2004) and short wave steepness (Baldock and Huntley, 2002; Baldock, 2012). Mild sloping beaches are conducive to bound infragravity waves which shoal strongly seaward of the breakpoint and have small wavelengths relative to the surf zone width. Whereas, breakpoint forced infragravity waves are more dominant on steep beaches where the wavelength of the short wave groups is large compared with the surf zone width.

It was long believed that infragravity waves reflect almost entirely from the shore giving rise to a cross-shore (quasi-)standing wave structure (Guza and Thornton, 1985). More recently, however, considerable infragravity wave dissipation close to shore has been observed in a number of field (e.g., Ruessink, 1998; Sheremet et al., 2002; Henderson et al., 2006; Guedes et al., 2013; De Bakker et al., 2014; Fiedler et al., 2015), laboratory (e.g., Battjes et al., 2004; Van Dongeren et al., 2007; De Bakker et al., 2015), and numerical modelling (e.g., Ruju et al., 2012; De Bakker et al., 2016) studies. Furthermore, a number of studies have observed runup saturation extending into the infragravity band on dissipative beaches and under highly energetic wave conditions (e.g., Ruggiero et al., 2004; Senechal et al., 2011; Guedes et al., 2013).

Several mechanisms have been proposed in the literature to explain the observed decay of infragravity wave energy close to shore. Henderson and Bowen (2002) suggested bottom friction as a dominant dissipation mechanism. However, unlike in coral reef environments where the bottom surface is comparatively rough (Pomeroy et al., 2012; Van Dongeren et al., 2013), bottom friction on sandy beaches has since been deemed a secondary dissipation mechanism at best (e.g., Henderson et al., 2006; Van Dongeren et al., 2007; De Bakker et al., 2014). Henderson et al. (2006) and Thomson et al. (2006), and several studies since, have shown that infragravity energy loss can result from non-linear energy transfers back to sea-swell frequencies through triad interactions. This process is most important on steeper beaches or in surf zone depths of more than ~1 m where sea-swell energy exceeds infragravity energy, but less so on gently sloping beaches where infragravity energy dominates in the inner surf zone and triad interactions tend to be between infragravity frequencies only (Guedes et al., 2013; De Bakker et al., 2014, 2015, 2016). These infragravity-infragravity interactions allow for the steepening of the infragravity wave which culminates in its breaking and thus considerable energy loss close to shore (e.g., Battjes et al., 2004; Van Dongeren et al., 2007; Lin and Hwung, 2012; De Bakker et al., 2014). Numerical modelling by Ruju et al. (2012) suggests that the observed infragravity wave energy loss can result from a combination of non-linear energy transfer to sea-swell frequencies in the outer surf zone and wave breaking closer to shore.

Based on bichromatic wave experiments, Van Dongeren et al. (2007) showed that the amplitude reflection coefficient R of infragravity waves at the shoreline is related to a normalised bed slope parameter β_H defined as

$$\beta_H = \frac{\beta T}{2\pi}\sqrt{\frac{g}{H^+}} \tag{1}$$

where β is bed slope, T is the infragravity wave period, g is gravitational acceleration, and H^+ is the height of the incoming infragravity wave. The normalised bed slope parameter is based on the premise that a given beach slope will have a higher effective steepness for low frequency (long) waves than it will for high frequency (short) waves. Van Dongeren et al. (2007) observed a transition at $\beta_H \approx 1.25$, below which waves experience a mild sloping regime and dissipate due to wave breaking, and above which waves experience a steep sloping regime and reflect with minimal dissipation. Using field data from a dissipative beach, De Bakker et al. (2014) observed a more gradual transition from mild to steep sloping regime occurring at $\beta_H \approx 3$, whereas numerical modelling by De Bakker et al. (2016) showed this transition occurring at $\beta_H \approx 4$.

The objective of this paper is to investigate the dependence of infragravity waves on offshore forcing parameters, with particular attention given to the magnitude and spatial variation of the infragravity energy flux in the surf zone during contrasting swell and wind-wave conditions. In doing so, this contribution extends the work of De Bakker et al. (2014) and other field studies that have largely been undertaken on low fetch coastlines and/or during low-moderate energy conditions. New field observations are presented of infragravity waves on a high energy, dissipative, fetch-unlimited beach under a wide variety of offshore wave conditions. Data collection methods and analysis techniques are described in Section 2. Results of infragravity wave forcing, propagation and reflection are presented in Section 3. These results are placed into context with previous findings in Section 4, and summarised in Section 5.

2. Methodology

2.1. Field site and data collection

Data were collected for 33 consecutive tidal cycles from 7 to 24 November 2014 at Perranporth Beach, Cornwall, UK (Fig. 1). Perranporth, situated at the southern end of Perran Sands, is a macrotidal, dissipative beach with a semi-diurnal tidal regime and a mean spring tidal range of 6.1 m. The intertidal region has an average cross-shore length of 500 m and a longshore extent of 1.2 km. Perranporth is a relatively straight beach facing west-northwest so is fully exposed to the dominant westerly wave approach, receiving both Atlantic swell and locally generated wind waves. The beach is characterised by a low-gradient ($\beta \approx 0.012$ over the intertidal region), concave profile composed of medium sand (D_{50}=0.30 mm). Most of the intertidal region is relatively featureless and alongshore homogeneous; however, well pronounced bar-rip morphology is exposed during spring low tides (Poate et al., 2014). Perranporth's relatively featureless profile, along with its cross-shore dominance and exposure to a wide range of swell and wind waves, make it an excellent site for studying infragravity wave behaviour under different levels of offshore forcing.

Pressure observations were logged continuously at 4 Hz by 15 in situ pressure sensors. The sensors were situated in a cross-shore array spanning 372 m (Fig. 2); 13 were located between the mean spring high and mean spring low tide lines and 2 were located slightly above the mean spring high tide line to capture inner surf zone data during periods of particularly energetic wave forcing that are typical for the time of year. The pressure sensors were securely attached to screw in