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# Energy transfers and reflection of infragravity waves at a dissipative beach under storm waves

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## Key Points:

- Very large IG waves are observed at a dissipative beach under a storm, long-period swell and are driven by the bound wave mechanism
- In the surf zone, IG wave energy is transferred not only towards superharmonic but also subharmonic frequencies
- IG wave reflection is tidally-modulated and almost full at high tide due to the increase in beach slope

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## Abstract

This study presents unpublished field observations of infragravity waves, collected at the dissipative beach of Saint-Trojan (Oléron Island, France) during the storm Kurt (03/02/2017), characterized by incident short waves of significant heights reaching 9.5 m and peak periods reaching 22 s. Data analysis reveals the development of exceptionally large infragravity waves, with significant heights reaching 1.85 m close to shore. Field observations are complemented by numerical modelling with XBeach, which well reproduces the development of such infragravity waves. Model results reveals that infragravity waves were generated mainly through the bound wave mechanism, enhanced by the development of a phase lag with the short wave energy envelope. Spectral analysis of the free surface elevation shows the generation of superharmonic and subharmonic infragravity waves, the latter dominating the free surface elevation variance close to shore. Modelling results suggest that subharmonic infragravity waves result, at least partly, from infragravity-wave merging, promoted by the combination of free and bound infragravity waves propagating across a several kilometer-wide surf zone. Due to the steeper slope of the upper part of the beach profile, observed and modeled reflection coefficients under moderate-energy show a strong tidal modulation, with a weak reflection at low tide ( $R^2 < 0.2$ ) and a full reflection at high tide ( $R^2 \sim 1.0$ ). Under storm waves, the observed reflection coefficients remain unusually high for a dissipative beach ( $R^2 \sim 0.5 - 1.0$ ), which is explained by the development of subharmonic infragravity waves with frequencies around 0.005 Hz, too long to suffer a substantial dissipation.

## 1 Introduction

Infragravity (hereafter IG) waves are surface gravity waves with frequencies typically ranging from 0.004 to 0.04 Hz, related to the presence of groups in incident short waves [see *Bertin et al.*, 2018, for a recent review]. IG waves are only a few mm to cm-high in the deep ocean [e.g. *Rawat et al.*, 2014; *Crawford et al.*, 2015; *Smit et al.*, 2018] but can exceed 1.0 m close to shore under storm conditions [*Ruessink*, 2010; *Fiedler et al.*, 2015; *Inch et al.*, 2017]. Although not validated against field observations, the application of XBeach [*Roelvink et al.*, 2009] to the SW of Oléron Island (France) by *Baumann et al.* [2017] even suggests that IG waves could exceed 2.0 m close to shore under very energetic, narrow-banded incident swells. Therefore, IG waves have an essential contribution to sandy beach [e.g. *Guza and Thornton*, 1982; *Elgar et al.*, 1992; *Reniers et al.*, 2002; *Ruessink et al.*, 1998a; *Guedes et al.*, 2013] and tidal inlet hydrodynamics [*Bertin and Olabarrieta*, 2016; *Bertin et al.*, 2019; *Mendes et al.*, 2020], sediment transport [e.g. *Russell*, 1993; *Aagaard and Greenwood*, 2008; *De Bakker et al.*, 2016a] and dune and barrier breaching [e.g. *Roelvink et al.*, 2009], particularly under storm waves.

At dissipative beaches, IG waves usually dominate the spectrum of the free surface elevation close to shore [*Guza and Thornton*, 1982; *Russell*, 1993; *Ruessink et al.*, 1998b] and therefore control the development of large runup [*Raubenheimer and Guza*, 1996; *Ruessink et al.*, 1998b; *Ruggiero et al.*, 2001] and overwash along the coast and subsequent washovers in low-lying zones [e.g. *Baumann et al.*, 2017]. At such gently-sloping beaches, IG waves are mostly generated through the bound wave mechanism, which corresponds to second-order nonlinear wave-wave interactions that result in the development of long waves, out of phase with the energy envelope of the short waves. This mechanism was first demonstrated analytically in 1D by *Biesel* [1952] and *Longuet-Higgins and Stewart* [1962] and was then extended to 2D random waves by *Hasselmann* [1962]. These analytical solutions imply that the frequency of the resulting IG waves should decrease under narrow-banded and long-period incident short waves. Yet, *Bertin and Olabarrieta* [2016] observed relatively short-period IG waves (e.g.  $T < 60$  s) under such incident short waves while other authors reported IG wave periods in the range 120 – 300 s under shorter period incident waves [e.g. *De Bakker et al.*, 2014; *Inch et al.*, 2017]. This apparent inconsistency suggests that the relationship between the shape of the incident short wave spectra and the frequency of IG waves is not straightforward. Also, these analytical solutions were derived considering a flat

69 bottom while for sloping bottoms, the bound waves increasingly lag behind the wave groups  
 70 as and when the water depth decreases. This phase lag was observed in both field [e.g. *List*,  
 71 1992; *Masselink*, 1995; *Inch et al.*, 2017] and laboratory experiments [*Battjes et al.*, 2004;  
 72 *De Bakker et al.*, 2013; *Padilla and Alsina*, 2017] and was demonstrated semi-analytically  
 73 [*Janssen et al.*, 2003; *Guérin et al.*, 2019]. *Van Dongeren et al.* [2007] showed that this phase  
 74 lag enhances energy transfer from short waves to IG waves. This process is often referred to  
 75 as "bound wave shoaling", which is somehow misleading because the resulting growth of IG  
 76 waves is higher than the growth associated with conservative shoaling (i.e. Green's Law).

77 In the surf zone, depth-induced breaking of short waves results in a shoreward reduction  
 78 of short wave groupiness, which allows for the release of IG waves that then propagate  
 79 as free waves [e.g. *Janssen et al.*, 2003; *Battjes et al.*, 2004]. *Baldock* [2012] proposed that  
 80 bound wave release can only occur if short waves are in the shallow-water regime when  
 81 breaking, which condition is not necessarily met under short period waves and/or storm  
 82 conditions. Throughout their propagation in the inner surf zone of gently sloping beaches,  
 83 IG waves transfer energy to higher frequencies and steepen, which promotes their dissipation  
 84 through depth-limited breaking [*Battjes et al.*, 2004; *Van Dongeren et al.*, 2007; *Lin and*  
 85 *Hwang*, 2012; *De Bakker et al.*, 2014]. Several authors reported the saturation of wave runup  
 86 in the IG band under storm waves [*Ruessink et al.*, 1998b; *Ruggiero et al.*, 2004; *Sénéchal*  
 87 *et al.*, 2011], possibly owing to IG wave dissipation close to shore. However, *Fiedler et al.*  
 88 [2015] did not observe any runup saturation under comparable incident conditions and beach  
 89 slope, suggesting that further research on IG wave dissipation is needed. IG wave energy  
 90 that is not dissipated in the surf zone can be reflected along the shore, a process that was  
 91 observed and quantified both in the field [*Huntley et al.*, 1981; *Guza and Thornton*, 1985;  
 92 *Elgar et al.*, 1994; *De Bakker et al.*, 2014; *Inch et al.*, 2017] and in laboratory experiments  
 93 [*Battjes et al.*, 2004; *Van Dongeren et al.*, 2007]. The reflection coefficient  $R^2$ , which cor-  
 94 responds to the ratio between the outgoing and the incoming IG wave energy, was shown  
 95 to increase with the beach slope and with the period of incident IG waves [*Van Dongeren*  
 96 *et al.*, 2007]. As sandy beaches often exhibit steeper slopes in their upper part, a tidal  
 97 modulation of IG wave reflection is expected and was already reported [*Okhiro and Guza*,  
 98 1995]. Recent observations of free IG waves across the shelf of Oregon even revealed that  
 99 such a tidal modulation can be strong in the deep ocean [*Smit et al.*, 2018]. The frequency-  
 100 dependence of IG wave dissipation and reflection processes produces large differences in the  
 101 cross-shore structure of surface elevation spectra. Indeed, higher frequency IG waves tend  
 102 to be progressive across the surf zone while lower frequencies tend to develop quasi-standing  
 103 patterns due to a stronger reflection [*De Bakker et al.*, 2014; *Inch et al.*, 2017].  
 104

105 In a recent review paper, *Bertin et al.* [2018] pointed out that further research on IG  
 106 waves was needed to better understand their generation mechanisms, their transformations  
 107 across the surf zone and their reflection along the coast. This study aims to contribute to  
 108 this effort and to answer more specifically the following questions: how large can IG waves  
 109 be in the nearshore? What is the relationship between the shape of the incident short-wave  
 110 spectra and the IG waves spectra along the coast? Do IG waves necessarily suffer strong  
 111 dissipation and subsequent low reflection at a dissipative beach? To address these questions,  
 112 we present the analysis of an unpublished dataset collected under storm-wave conditions at a  
 113 dissipative beach located to the SW of Oléron island (France), complemented with numerical  
 114 modelling using XBeach [*Roelvink et al.*, 2009].

## 115 2 Study area

116 This study takes place at Saint-Trojan Beach, a dissipative beach located in the cen-  
 117 tral part of the French Atlantic coast (Figure 1), along the south-western coast of Oléron  
 118 Island. This stretch of coast corresponds to a 8 km-long sandspit, bounded to the South by  
 119 the Maumusson Inlet [*Bertin et al.*, 2005]. The continental shelf in front of the study area  
 120 is about 150 km-wide, with a very gently sloping shoreface, the isobath 20 m being found



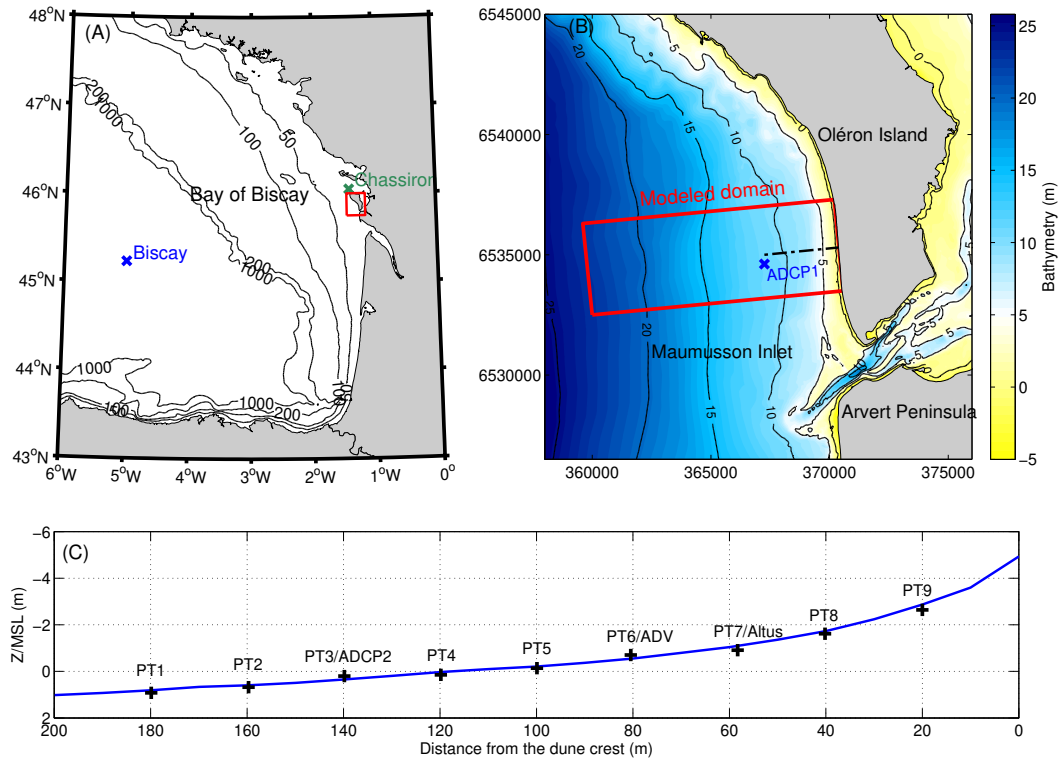
121 about 10 km away from the shoreline. The tidal regime in this region is semi-diurnal and  
 122 macrotidal, with a tidal range varying between about 1.5 m during neap tides and 5.5 m dur-  
 123 ing spring tides. Tidal currents remain weak at the studied beach and the impact of tides on  
 124 short waves remains mostly restricted to water level variations. According to *Bertin et al.*  
 125 [2008], yearly-mean deep water wave conditions are characterized by a significant height  
 126 ( $H_s$ ) of 2 m, a peak period ( $T_p$ ) of 10 s and a mean direction of  $285^\circ N$ . During storms,  $H_s$   
 127 can reach episodically 10 m in deep water and  $T_p$  can exceed 20 s with a westerly direction  
 128 [*Bertin et al.*, 2015]. Due to the very gently sloping shoreface and the wide continental shelf,  
 129 the most energetic waves suffer strong dissipation and numerical wave models suggest that  
 130 their  $H_s$  hardly exceeds 5 m at the breaking point [*Bertin et al.*, 2008].

132 The studied beach is mainly composed of fine and well sorted sands ( $d_{50} = 0.18 -$   
 133  $0.22$  mm), which together with the energetic wave climate and the macrotidal range cause  
 134 its morphology to be non-barred and dissipative (Figure 1-B). Small-amplitude intertidal  
 135 bars can only develop after the persistence of fair weather conditions. Its slope typically  
 136 ranges from about 0.0015 at the shoreface to 0.015 in the intertidal area [*Bertin et al.*,  
 137 2008], although a berm usually develops during the course of the summer period, with a  
 138 slope reaching 0.04. Due to the persistence of low to moderate-energy wave conditions in  
 139 autumn 2016 and early winter 2017, such a berm was still present during our field campaign.  
 140 This gently sloping morphology and the presence of a shallow shoreface induce a strong wave  
 141 refraction, so that the wave angle at breaking is usually small, with typical values smaller  
 142 than  $10^\circ$  [*Bertin et al.*, 2008].

### 150 3 Field campaign and data processing

151 The field campaign presented in this study was motivated by the development of the  
 152 storm Kurt, which started to deepen to the SE of the Newfoundland on the 31/01/2017 and  
 153 crossed the North Atlantic Ocean following an Eastward track, centered between  $48^\circ$  and  
 154  $50^\circ$ . Based on the CFSR reanalysis [*Saha et al.*, 2010], Kurt reached a minimum sea-level  
 155 pressure around 955 mbar on the 02/02/2017 about 1000 km to the West of the Bay of Bis-  
 156 caya, accompanied with a  $\sim 500$  km-wide band of western winds in the range  $25 - 35 \text{ m}\cdot\text{s}^{-1}$ .  
 157 This atmospheric setting drove a very large and long period swell, that reached the French  
 158 coasts in the night of the 02/02/2017 to the 03/02/2017. At the deep water buoy of Biscay  
 159 (Figure 1-A), the mean wave period increased from 8.0 s to 13.0 s and  $H_s$  rapidly increased  
 160 from 3.0 m to almost 10.0 m, which value corresponds to a return period on the order of  
 161 one year [*Nicolae-Lerma et al.*, 2015]. The wave hindcast described in *Guérin et al.* [2018]  
 162 suggests that the wave peak period  $T_p$  exceeded 20 s. The measurement period encompassed  
 163 four tidal cycles, from the 01/02/2017 to the 03/02/2017, characterized by a tidal range of  
 164 3.5 to 4 m. An Acoustic Doppler Current Profiler (ADCP1) with a frequency of 600 kHz  
 165 and equipped with a pressure sensor was deployed about 3 km offshore (Figure 1-B). In the  
 166 intertidal zone, 9 pressure transducers (PT) sampling at 4 Hz were deployed (Figure 1-C) as  
 167 well as a second ADCP (ADCP2), with a head frequency of 2 MHz mounted with a pressure  
 168 sensor at the location of PT3. The PTs were buried between 0.05 to 0.10 m of sand, in  
 169 order to avoid dynamic pressure errors. The position of each sensor was measured with a  
 170 differential GNSS, using a post-processing technique with a base station settled on the dune  
 171 crest in front of the instrumented profile [*Guérin et al.*, 2018]. This GNSS was also used to  
 172 survey the intertidal beach topography at every low tide. The analysis of this data revealed  
 173 surprisingly small morphological changes for storm wave conditions, typically lower than  
 174 0.1 m along the cross-shore profile of the instruments.

175 For each sensor, bottom pressure measurements were first corrected for sea level atmo-  
 spheric pressure measured at the nearby meteorological station of Chassiron (Figure 1-A).  
 The entire record was split into consecutive bursts of 30 min and only the bursts in which the



144 **Figure 1.** (A) Location of the study area in the Bay of Biscay, with the Biscay buoy (✖) and  
 145 Chassiron Meteorological station (✖). (B) Detailed bathymetry of the study area (m relative to  
 146 mean sea-level), showing the location of the offshore ADCP1 (✖) and the instrumented cross-shore  
 147 profile (dashed line). The coordinates are in meter (Lambert-93 projection) (C) Zoom-in on the  
 148 intertidal part of the instrumented cross-shore profile, showing the location of the instruments used  
 149 in this study (+) with respect to the beach topography (blue line).

sensor was continuously submerged were considered. PT9 was never continuously submerged during more than 30 minutes and was therefore discarded for the present study. Bottom pressure power density spectra  $E_p(f)$  were computed using Fast Fourier Transforms, with 10 Hanning-windowed, 50% overlapping segments (20 degrees of freedom). These pressure spectra were then converted into elevation spectra  $E(f)$  considering linear wave theory [see for instance *Bishop and Donelan, 1987*]. The spectral significant wave height ( $H_{m0}$ ) was computed as:

$$H_{m0} = 4\sqrt{m_0} \quad (1)$$

with

$$m_0 = \int_{f_{min}}^{f_{max}} E(f) df \quad (2)$$

where  $f_{max}$  was set to 0.4 Hz, a value for which the pressure correction reaches about 13 by 3 m water depth, well below the threshold of 100 to 1000 recommended by *Bishop and Donelan* [1987].  $f_{min}$  is time-varying and defined following *Roelvink and Stive* [1989] or *Hamm and Peronnard* [1997] as half the continuous peak frequency  $f_p$ , computed from the offshore ADCP data as:

$$f_p = \frac{m_0^2}{m_{-2} m_1} \quad (3)$$

where

$$m_k = \int_{f_{min}}^{f_{max}} f^k E(f) df \quad (4)$$

176 The continuous peak frequency was preferred to the discrete one because it is a more  
 177 stable parameter, particularly under multimodal sea states, as it was the case at the begin-  
 178 ning of the field campaign. As the incident peak period doubled during the field campaign,  
 179 a fixed frequency cutoff would not have allowed for a proper separation between the gravity  
 180 and the IG bands. In order to characterize the spatio-temporal variations of incoming IG  
 181 wave frequencies, the mean IG wave period  $T_{m02,IG+}$  was also computed based on the in-  
 182 coming IG wave signal, separated from the outgoing one at the ADCP2 and the ADV using  
 183 the method of *Guza et al.* [1984]:

$$T_{m02,IG+} = \sqrt{\frac{m_0}{m_2}} \quad (5)$$

## 184 4 Numerical modelling

### 185 4.1 Model description

186 XBeach is a two-dimensional modelling system that couples a Saint-Venant solver with  
 187 a simplified wave-action model and a sediment transport model to simulate the generation  
 188 and propagation of IG waves and the associated dynamics [*Roelvink et al., 2009*]. Based on  
 189 directional wave spectra provided along the open boundary, XBeach applies random phase  
 190 summation to reconstruct time series of the free surface elevation. A Hilbert transform  
 191 is applied to derive time-series of short-wave energy varying at the scale of wave groups  
 192 and imposed as boundary conditions in the wave action model. IG waves are represented  
 193 explicitly in the Saint-Venant model and are forced by the gradient of wave radiation stress  
 194 computed from the wave model. The incoming bound-wave is computed following *Herbers*  
 195 *et al.* [1994] and is imposed along the open boundary of the Saint-Venant model.

### 196 4.2 Model implementation

197 A rectilinear grid centered on the instrumented cross-shore profile and extending  
 198 4000 m in the alongshore direction was implemented. In the cross-shore direction, this grid  
 199 starts from the dune crest and extends 11000 m offshore, corresponding to a mean water  
 200 depth of about 23 m (Figure 1-B). The spatial resolution ranges from 20 m along the open

201 boundary to 1 m in the beach upper part (Figure 1-B). A sensitivity analysis revealed that  
 202 such a fine resolution was required to adequately represent IG waves in shallow water and  
 203 their reflection along the shoreline. Along the offshore open boundary, XBeach was forced  
 204 with time series of water levels recorded at ADCP1 (Figure 1-B). The wave model was  
 205 forced with time-series of directional wave spectra, originating from a regional application  
 206 of the WaveWatchIII model [Tolman, 2009] forced by wind fields from the CFSR reanalysis  
 207 [Saha *et al.*, 2010]. In deep water, Guérin *et al.* [2018] showed that this wave hindcast  
 208 resulted in a normalized root mean squared discrepancy (hereafter NRMSD) of 10% for  
 209  $H_{m0}$  and 6% for the mean wave period. Bottom friction was represented by a quadratic  
 210 bottom shear stress with a constant Chezy coefficient set to  $80 \text{ m}^{0.5} \cdot \text{s}^{-1}$ . The horizontal  
 211 eddy viscosity was assumed constant ( $0.5 \text{ m}^2 \cdot \text{s}^{-1}$ ) and the minimum water depth was set  
 212 to 0.01 m. Depth-limited breaking in the wave model was represented using the model of  
 213 Roelvink [1993a] with a breaking index  $\gamma$  adjusted to 0.38 after calibration. The model was  
 214 run for the duration of the field experiment (3 days), and time series of short wave height,  
 215 surface elevation and current velocities were archived at 2 Hz. In order to get insights into  
 216 IG wave generation mechanisms, additional numerical experiments were performed, where  
 217 wave forces were switched off either inside or outside the surf zone. The breaking formulation  
 218 of Roelvink *et al.* [2009] was used to determine whether a computational node was located  
 219 inside or outside the surf zone, i.e. if the local wave height was not exceeding the threshold  
 220  $H_{max}$  as defined in Roelvink [1993b]. In the bound wave case, wave forces were turned off  
 221 inside the surf zone while in the breakpoint case, wave forces were turned off outside the  
 222 surf zone and the incoming boundwave was not included along the open boundary, follow-  
 223 ing Pomeroy *et al.* [2012] and Bertin and Olabarrieta [2016]. Lastly, additional 24 h-long  
 224 simulations were run with constant water levels and wave forcing at specific times of the  
 225 measurement period to provide sufficient resolution and number of degrees of freedom for  
 226 spectral and bispectral analysis used to investigate IG wave energy transfers through non-  
 227 linear triad coupling. Spectral estimates were computed following the same methodology  
 228 as for the field observations (section 3). Due to the random phase summation technique, a  
 229 substantial scatter in terms of IG waves can be observed from one simulation to another. For  
 230 model/data comparisons, bulk parameters computed from field observations were compared  
 231 against the mean of a model ensemble of 10 realizations.

### 233 4.3 Model post-processing

234 Incoming and outgoing IG waves along the studied cross-shore profile were separated  
 235 using a Radon transform [Radon, 1917]. This technique projects the two-dimensional wave  
 236 field (here space corresponds to the studied cross-shore profile and time to 1800 s-long sam-  
 237 ples) into polar space [Yoo *et al.*, 2011]. The Radon transform is a powerful tool to study  
 238 nearshore waves as it allows the separation of incoming and outgoing wave fields on high-  
 239 resolution data sets without any hypotheses on the hydrodynamics [e.g. Almar *et al.*, 2014;  
 240 Martins *et al.*, 2017]. The energy conservation properties of the method were assessed by  
 241 examining the ratio of energy computed using the sum of the separated signals and that of  
 242 the original total signal. The relative difference never exceeded 4% and was 1.4% on average  
 243 over the simulated period. Reflection coefficients  $R^2$  were computed as the ratio between  
 244 the outgoing and the incoming IG wave energy.

246 In order to analyze IG-wave generation mechanisms, the phase lag between the short  
 247 wave energy envelope  $A$  and incoming IG waves  $\eta^+$  was estimated using cross-spectral  
 248 analysis:

$$\phi_{f,x} = \arctan \left[ \frac{\mathcal{I}\{Cr_{A,\eta^+}(f,x)\}}{\mathcal{R}\{Cr_{A,\eta^+}(f,x)\}} \right] \quad (6)$$

249 where  $Cr$  is the cross-spectrum of the short wave envelope  $A$  and the incoming IG waves  $\eta_+$ ,  
 250 separated along the studied cross-shore transect using the Radon transform described above  
 251 and  $\mathcal{I}$  and  $\mathcal{R}$  are the imaginary and the real parts of the cross-spectrum. As this method  
 252 provides a phase lag per frequency, the averaged values over the IG band (0.005 – 0.04 Hz)  
 253 were considered, which eliminates the problem of selecting arbitrarily a single frequency  
 254 while providing more stable phase lag estimates.

255 Possible energy transfers in the IG band were investigated through bispectral analysis,  
 256 a technique originally introduced by *Hasselmann et al.* [1963] and then used in numerous IG  
 257 wave studies [e.g. *Elgar and Guza*, 1985; *De Bakker et al.*, 2015]. Source terms for nonlinear  
 258 energy transfers between frequencies  $S_{nl}$  were computed using the stochastic formulation of  
 259 the second order nonlinear wave interaction theory of *Herbers et al.* [2000]:

$$S_{nl,f} = \frac{3\pi f}{h} \mathcal{I} \left\{ \left( \sum_{f'=0}^f \Delta f B_{f',f-f'} - 2 \sum_{f'=0}^{f_N-f} \Delta f B_{f',f} \right) \right\}. \quad (7)$$

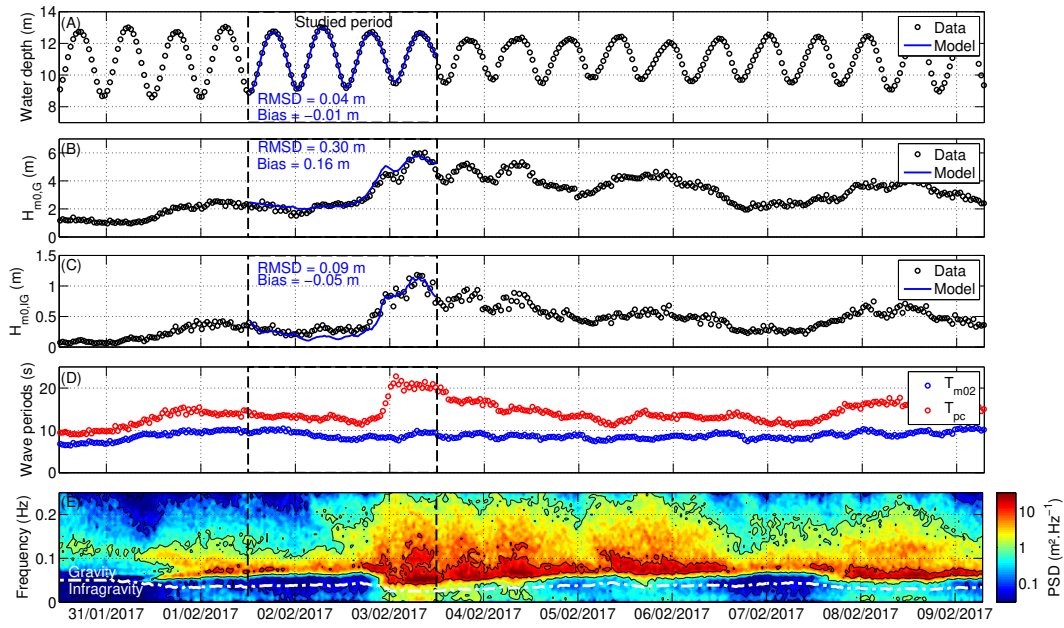
260 where the term  $\sum_{f'=0}^f B_{f',f-f'}$  represents the sum interactions in the imaginary part of  
 261 the bispectrum  $B$ , and the term  $-2 \sum_{f'=0}^{\infty} B_{f',f}$  represents the difference interactions, as a  
 262 particular frequency can contribute simultaneously to both difference and sum interactions.  
 263 The 24-h analyzed model samples allow computing these terms with 602 degrees of freedom  
 264 and a spectral resolution of 0.0019 Hz. Further details on these analysis techniques can be  
 265 found in *Bertin et al.* [2018].

## 266 5 Results

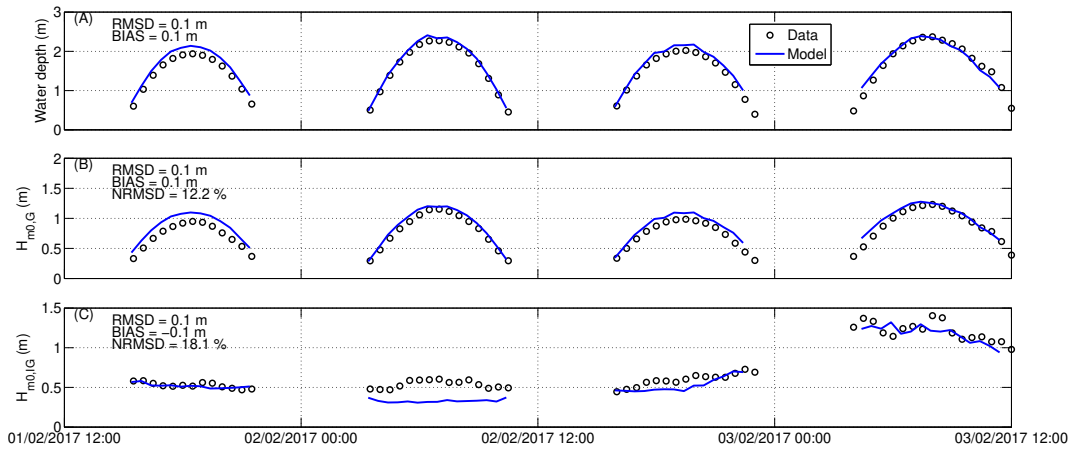
### 267 5.1 Characterization of short waves and IG wave heights

268 As explained above, the field campaign presented in this study was motivated by the  
 269 development of the storm Kurt, which generated offshore  $H_s$  of the order of 10.0 m with  $T_p$   
 270 over 20 s. At the ADCP1 (Figure 1-A), the spectral significant wave height in the gravity  
 271 band (hereafter  $H_{m0,G}$ ) increased from 2.0 m at the beginning of the campaign to a max-  
 272 imum of 6.0 m on the 03/02/2017 (Figure 2-B). Over the same period,  $T_p$  increased from  
 273 10 – 15 s to more than 20 s. The increase in  $H_{m0,G}$  is well captured by XBeach, with a  
 274 RMSD of 0.3 m and a NRMSD below 10%. In more detail,  $H_{m0,G}$  is tidally modulated  
 275 during the last tidal cycle, which suggests that the surf zone at low tide extended offshore  
 276 of the ADCP1, located more than 3000 m from the shoreline. At the sensors deployed in  
 277 the intertidal zone (PT1 to PT9), wave heights were depth-limited and therefore strongly  
 278 tidally-modulated, with  $H_{m0,G}$  roughly equal to half of the water depth (Figure 3). Wave  
 279 heights are well reproduced by XBeach, with a mean RMSD of 0.12 m over the 8 intertidal  
 280 sensors, which results in a NRMSD of 15% (Figure 5-A). *Guérin et al.* [2018] obtained  
 281 slightly better predictions using an adaptive wave breaking parameterization, where the  
 282 breaking index  $\gamma$  increases with the bottom slope. Such a parameterization is not available  
 283 in XBeach and is in any case questionable for a spectral model resolving wave groups [e.g.  
 284 *Roelwink*, 1993a].  
 285

293 Very large IG waves developed during the last tidal cycle, which corresponds to the  
 294 arrival of the large swell generated by the storm Kurt. At the ADCP1 (Figure 1-B),  $H_{m0,IG}$   
 295 ranged from 0.25 to 0.5 m during the first three tidal cycles and increased to a maximum  
 296 of 1.2 m (Figure 2), a value undocumented for a water depth of 13 m.  $H_{m0,IG}$  are well  
 297 reproduced by XBeach, except during the second tidal cycle, where an underestimation by  
 298 a factor of 2 can be observed (Figure 2). In the intertidal zone, IG waves also increased  
 299 from about 0.5 m during the first three tidal cycles to a maximum of 1.85 m at PT6, with



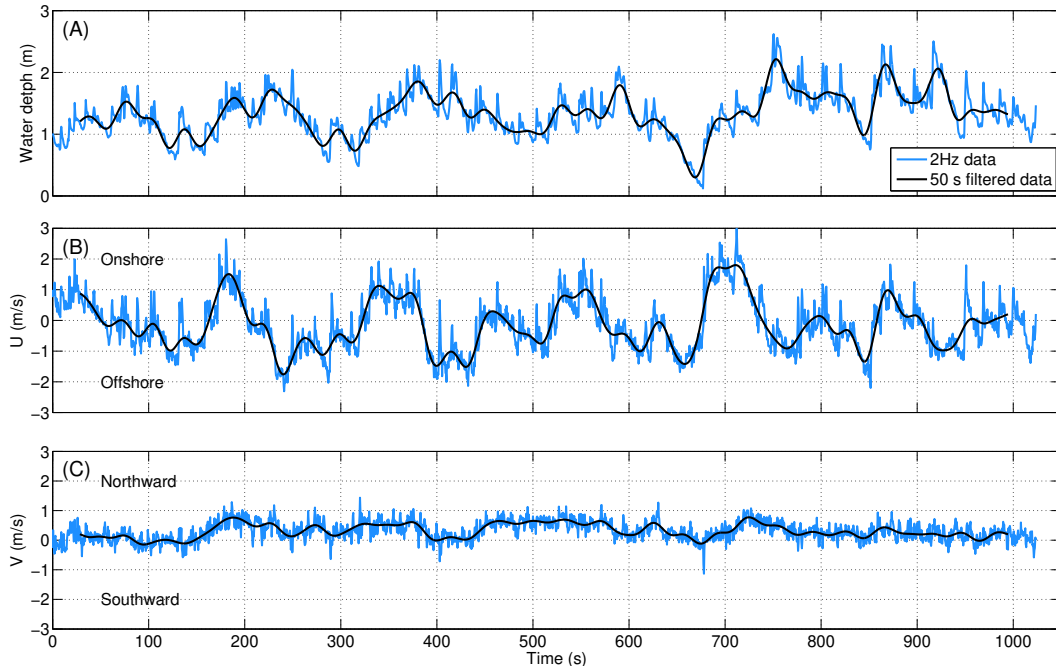
286 **Figure 2.** Time series of observed (circles) and modeled (solid lines) bulk parameters and spectra  
 287 at the location of the ADCP1 (Figure 1-B): (A) water depth; (B)  $H_{m0}$  in the gravity band; (C)  $H_{m0}$   
 288 in the IG band; (D) continuous peak (red) and mean (blue) wave periods and (E) power density  
 289 spectra of observed water levels computed, where the white dashed line corresponds to the adaptive  
 290 frequency cutoff between gravity and IG bands as described in section 3.



291 **Figure 3.** Modelled (blue line) against observed (black circle) water depth (A),  $H_{m0}$  in the  
 292 gravity (B) and in the IG (C) bands at PT3/ADCP2.



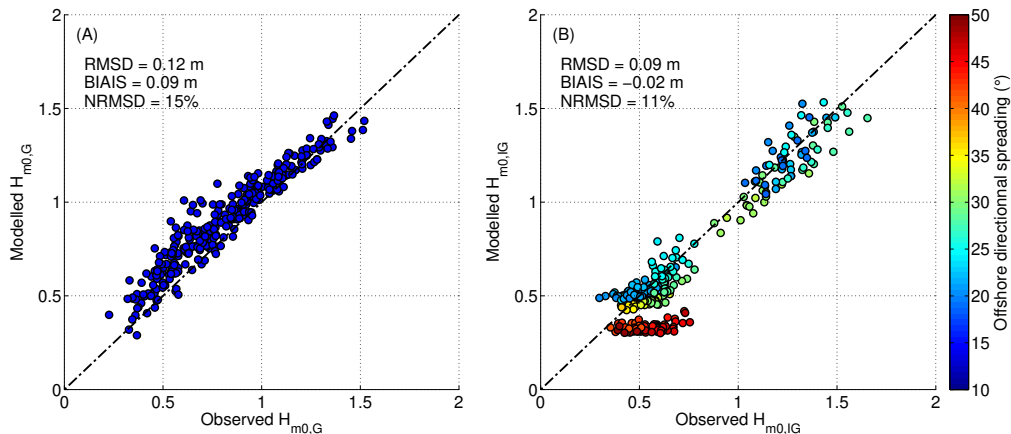
300 individual IG waves exceeding 2.5 m (not shown). Figure 4 shows an example of time series  
 301 of measured water depth at the ADCP2 (Figure 4-A), where the low-pass filtered signal  
 302 reveals that individual IG waves exceeded 2.0 m and induced cross-shore velocities ranging  
 303 from  $-2.0 \text{ m.s}^{-1}$  (offshore) to  $+2.0 \text{ m.s}^{-1}$  (onshore)(Figure 4-B). This figure also shows that  
 304 alongshore velocities were much weaker (Figure 4-C), with the ratio of the alongshore over  
 305 the cross-shore IG velocity variance being lower than 10%. The extension of this analysis to  
 306 the whole ADCP2 dataset reveals this ratio is about  $19 \pm 8\%$  (where  $\pm$  corresponds to one  
 307 standard deviation), which means that the IG wave dynamics was dominated by cross-shore  
 308 motions.



309 **Figure 4.** Time series of water depth (A), near bottom cross-shore (B) and longshore velocity  
 310 (C) at 2 Hz (blue) and low-pass filtered (black), measured at the ADCP2/PT3 (Figure 1-C) on the  
 311 03/02/2017 at 5h00.

315  $H_{m0,IG}$  are well reproduced by XBeach, except during the second tidal cycle where a  
 316 0.2 m negative bias can be observed (Figure 3), a problem that is also found at the ADCP1  
 317 (Figure 2-C). Considering the whole set of intertidal sensors,  $H_{m0,IG}$  are reproduced by  
 318 XBeach with a RMSD of 0.14 m, which corresponds to a NRMSD of 20% (Figure 5-B). To  
 319 be more specific,  $H_{m0,IG}$  are particularly underestimated when the incident short waves  
 320 have a large directional spreading (i.e.  $> 35^\circ$ , Figure 5-B), which occurred mainly during  
 321 the second tidal cycle (Figure 3). While discarding model results for such conditions, the  
 322 RMSD drops to 0.08 m and the NRMSD to 11%, which corresponds to high predictive  
 323 skills compared to previously published studies that provide a detailed validation of XBeach  
 324 [e.g. *Van Dongeren et al.*, 2013; *Bertin and Olabarrieta*, 2016; *Lashley et al.*, 2018]. The  
 325 underestimation of IG waves for broad short wave spectra is related to the original surfbeat  
 326 approach of Xbeach, where the wave energy from different directional bins is simply added  
 327 up, without considering the interference of the different wave components [*Roelvink et al.*,  
 328 2018]. To overcome this problem, *Roelvink et al.* [2018] recently proposed an alternative  
 329 approach, where the mean wave directions are calculated first and the short wave energy  
 330 is then propagated along these directions. However evaluating the recent improvements of





312 **Figure 5.** Modelled against observed  $H_{m0}$  in the gravity (A) and in the IG (B) bands, where  
 313 symbol color corresponds to the directional spreading of the incident short waves at the open  
 314 boundary of the modeled domain (Figure 1-C).

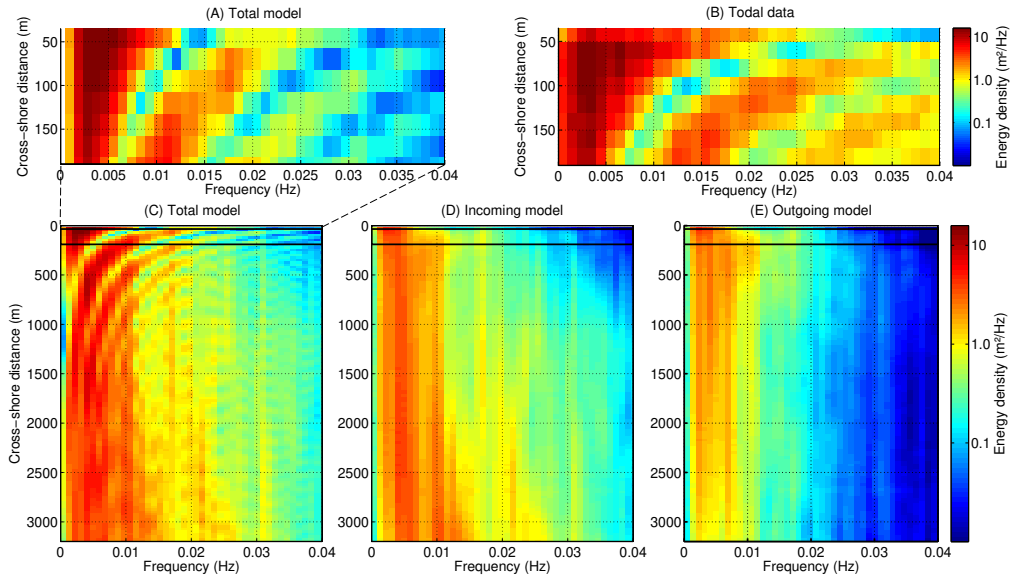
331 XBeach is outside the scope of this study, focused on the physical processes associated with  
 332 IG waves.

## 333 5.2 Frequency repartition of IG wave energy

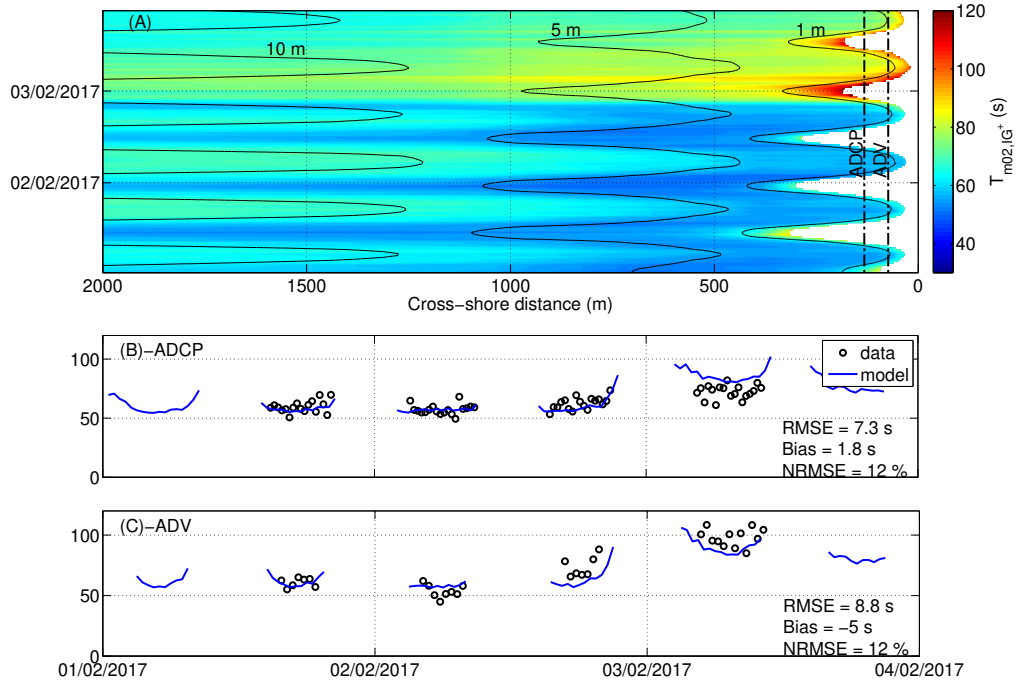
334 In order to investigate the evolution of the IG wave energy frequency repartition with  
 335 a sufficient spectral resolution, we analyzed 3 h-long time-series of modeled and observed  
 336 water depth, centered on the high tide of the last tidal cycle (storm Kurt). Incoming and  
 337 outgoing modeled IG waves were separated using a Radon transform (section 4.3) but the  
 338 number of intertidal sensors was too limited to apply this technique to field measurements.

342 Figure 6-A and 6-B show similarities between the modeled and the observed spatio-  
 343 frequential patterns of IG wave energy in the intertidal zone, with a main peak between 0.01  
 344 and 0.015 Hz, a super-harmonic peak around 0.02 and 0.025 Hz and a subharmonic peak be-  
 345 tween 0.001 and 0.005 Hz. From the beach lower part to the beach upper part, these three  
 346 peaks slide towards higher frequencies and the lower frequency one totally dominates the  
 347 power density spectra along the shoreline. Such intriguing patterns were already observed  
 348 in laboratory experiments of IG waves [Battjes *et al.*, 2004; Buckley *et al.*, 2018] and short  
 349 waves [Martins *et al.*, 2017] and are explained by interference between incoming and out-  
 350 going IG waves, creating nodes and antinodes, whose position with respect to the shoreline  
 351 varies with the IG wave frequency and the bottom slope. Figure 6-D and 6-E corroborate  
 352 this hypothesis and show that this pattern disappears in the modeled spectra corresponding  
 353 to the incoming and outgoing signals. The analysis of the modeled spectra for the incoming  
 354 signal (Figure 6-D) reveals that, at the shoreface, IG wave energy is mostly located around  
 355 a first peak at 0.01 Hz and a second broader peak centred around 0.005 Hz. A superhar-  
 356 monic secondary peak is also present around 0.02 Hz. Approaching the shoreline, IG wave  
 357 energy at higher frequencies decreases while most of the energy is located between 0.002  
 358 and 0.006 Hz. The spectra of the outgoing signal (Figure 6-E) suffer less transformation  
 359 and, compared to the incoming signal, display much less energy at frequencies above 0.015  
 360 to 0.02 Hz.

365 This analysis was extended to the whole studied period based on the mean incoming  
 366 IG wave period  $T_{m02,IG+}$  (Figure 7-A), computed from the incoming IG wave signal. For  
 367 moderate-energy wave conditions, this figure shows that  $T_{m02,IG+}$  first decreases from about



339 **Figure 6.** Spatio-frequential repartition of IG wave power spectral density modeled (A) and  
 340 observed (B) for the total signals in the intertidal zone and modeled along the studied cross-shore  
 341 transect for the total (C), the incoming (D) and the outgoing (E) signals.

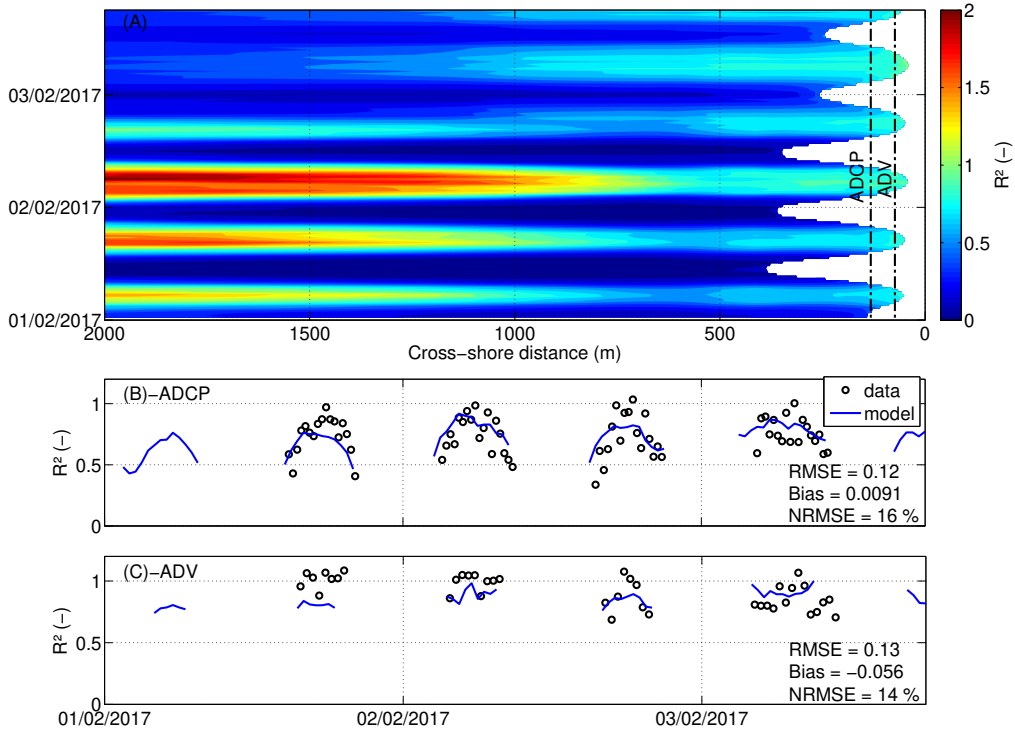


362 **Figure 7.** (A) Spatio-temporal repartition of incoming mean IG wave period  $T_{m02,IG+}$  along  
 363 the studied cross-shore transect. Modeled against observed time-series of  $T_{m02,IG+}$  and the ADCP2  
 364 (B) and the ADV (C).

368 60 to 70 s in 10 m water depth to about 50 s in 2 m water depth. For a given location along  
 369 the studied cross-shore profile,  $T_{m02,IG^+}$  exhibits therefore a substantial tidal modulation.  
 370 In water depth less than 1 m,  $T_{m02,IG^+}$  increases back to 60 – 70 and even over 80 s at low  
 371 tide (Figure 7). Under storm wave conditions (3/02/2017), a different behaviour is observed,  
 372 with a continuous increase in  $T_{m02,IG^+}$  from about 70 s in 10 m water depth to 90 – 100 s  
 373 in 2 m water depth. In water depth less than 1 m,  $T_{m02,IG^+}$  further increases up to 120 s at  
 374 low tide. The modeled temporal evolution of  $T_{m02,IG^+}$  fairly matches the observations at  
 375 the location of the ADCP2 and ADV, with a RMSD of 8 s, corresponding to a 12% error.

### 376 5.3 Reflection

377 The comparison between observed and modeled reflection coefficient  $R^2$  shows a good  
 378 agreement in the intertidal zone, with a RMSD of 0.12, corresponding to a normalized  
 379 error of about 15% (Figure 8-B and -C). Under moderate-energy incident short waves, both  
 380 modeled and observed  $R^2$  show a strong tidal modulation, with values below 0.2 at low  
 381 tide and close to 1.0 at high tide, suggesting full reflection along the waterline. This tidal  
 382 modulation substantially weakens under storm wave conditions, with  $R^2$  above 0.5 at low  
 383 tide along the waterline.



384 **Figure 8.** (A) Spatio-temporal variations of reflection coefficients  $R^2$  computed over the studied  
 385 period using a Radon transform [Radon, 1917] and modeled (blue) against observed (circles) time-  
 386 series of  $R^2$  at the ADCP2 (B) and the ADV (C).

387 Such a tidal modulation of  $R^2$  was already reported by *Okihiro and Guza* [1995], who  
 388 explained the higher reflection at high tide by the steeper slope of the beach upper part.  
 389 In the present study, the beach slope increases from about 1:100 in the lower part of the  
 390 intertidal zone to 1:25, which could directly explain the observed tidal modulation of IG wave  
 391 reflection. *Battjes et al.* [2004] proposed that IG wave reflection is related to a normalized  
 392 beach slope parameter  $\beta_H$ , defined as:

$$\beta_H = \frac{\beta}{\omega} \sqrt{\frac{g}{H}}, \quad (8)$$

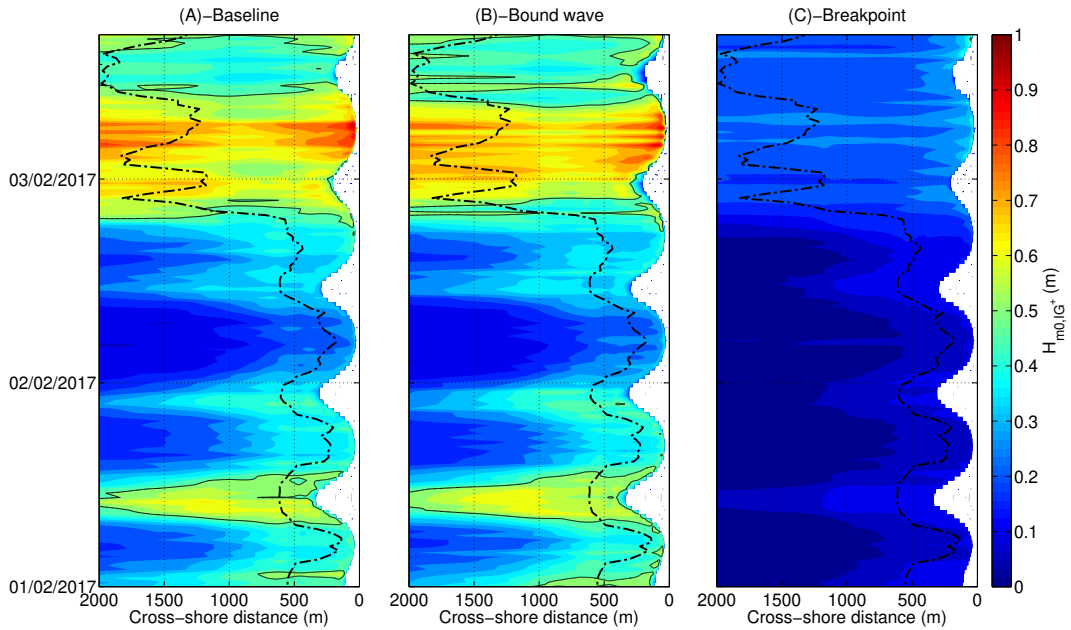
393

394 where  $\beta$  is the beach slope,  $\omega$  is the IG wave angular frequency,  $g$  is the gravitational  
 395 acceleration and  $H$  corresponds to the height of the incoming IG wave. According to  
 396 these authors, a large reflection would occur for  $\beta_H$  substantially above unity. Considering  
 397 incoming IG waves of height 0.5 m and frequency 0.01 Hz,  $\beta_H$  would increase from about  
 398 0.7 at low tide to 3.0 at high tide, which explains the observed tidal modulation of  $R^2$ .  
 399 Outside the surf zone, model results suggest  $R^2$  well above unity at high tide, which was  
 400 already observed in the field by *Elgar et al.* [1994] and *Sheremet et al.* [2002]. These authors  
 401 interpreted this behaviour by the fact that IG waves were gaining energy between their  
 402 sensors and the shoreline, before being reflected from a steep beach face.

## 403 6 Discussion

### 404 6.1 Generation mechanisms

405 The IG waves observed during our field campaign correspond to the largest values  
 406 reported in the literature [*Ruessink, 2010; Fiedler et al., 2015; Inch et al., 2017*], while our  
 407 adaptive frequency cutoff to separate gravity and IG bands is more conservative than the  
 408 fixed frequency cutoff used in these studies. At gently sloping beaches, it is usually admitted  
 409 that IG waves are generated through the bound wave mechanism [*Battjes et al., 2004; Inch*  
 410 *et al., 2017; Bertin et al., 2018*].

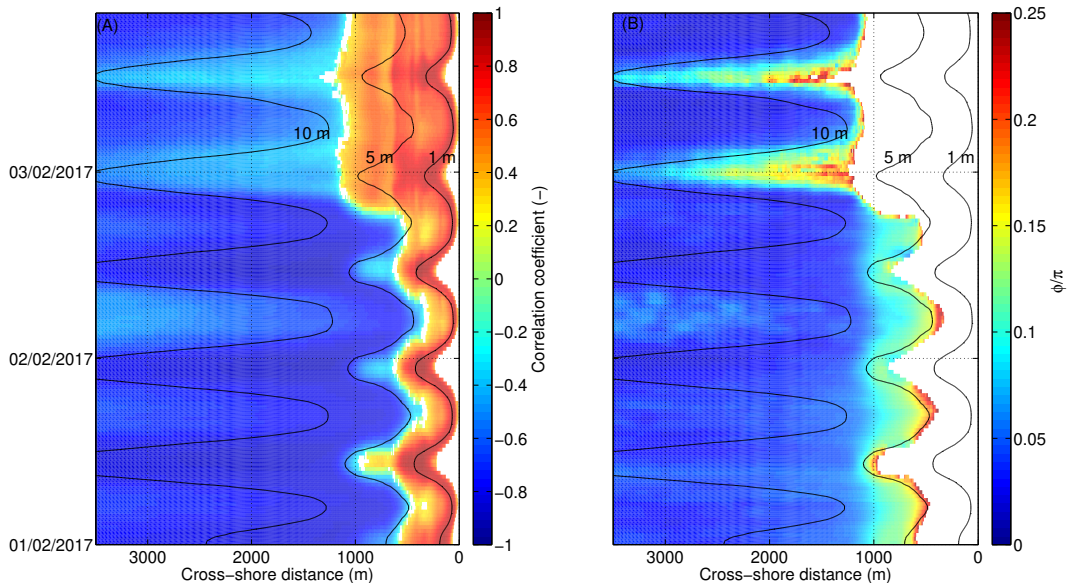


411 **Figure 9.** Modeled incoming IG wave height  $H_{m0,IG+}$  in the baseline simulation (A), the bound  
 412 wave case (B) and the breakpoint case (C). The black dotted line corresponds to the offshore limit  
 413 of the surf zone, as defined in section 4.2

414 Considering the analytical solution proposed by *Hasselmann* [1962] to compute the  
 415 bound wave based on directional wave spectra, energy transfers from the gravity band to the  
 416 IG band increase when the wave energy is large and distributed over narrow spectra.

417 Therefore, the very energetic and narrow-banded swell associated with the storm Kurt  
 418 would directly explain the development of such large IG waves. In order to verify this  
 419 hypothesis, we compared the incoming IG wave heights  $H_{m0,IG+}$  computed from our baseline  
 420 simulation with those computed from simulations where only either the bound wave or the  
 421 breakpoint mechanisms were represented (see section 4.2). This comparison reveals only  
 422 modest differences between the baseline simulation (Figure 9-A) and the simulation where  
 423 only the bound wave is considered (Figure 9-B). Conversely, the simulation where only  
 424 the breakpoint mechanism is considered (Figure 9-C) shows much smaller IG waves, with  
 425  $H_{m0,IG+}$  ranging from 0.1 to 0.2 m during first three tidal cycles and 0.4 m around the  
 426 peak of the storm. This analysis confirms that IG waves were mostly generated through  
 427 the bound wave mechanism, independently from the tidal phase or the incident short-wave  
 428 energy.

429 In accordance with this first finding, the modeled incoming IG waves are negatively  
 430 correlated with the short wave energy envelope (hereafter WEE, Figure 10-A). Strongest  
 431 correlations are found from the breaking point up to water depths of about 12 m, with  
 432 coefficients ranging from -0.4 to -0.9 over the studied period (always significant at 95%,  
 433 mean  $-0.54 \pm 0.16$ ). In more details, the strongest negative correlations are not found at  
 434 zero lag and incoming IG waves are lagging behind the WEE by a few seconds. Figure 10-B  
 435 shows the modeled spatio-temporal evolution of the normalized phase lag between incoming  
 436 IG waves and the WEE, shifted by  $\pi$  for the sake of readability. For moderate-energy incident  
 437 conditions, this phase lag continuously increases from about  $\pi/20$  by 10 m water depth to  
 438 about  $\pi/5$  by 4 m water depth, which corresponds to the beginning of the surf zone. In  
 439 the inner surf zone, the correlation cancels out and then switches to positive (Figure 10-A),  
 440 due to the modulation of short wave heights by IG waves, a process that is well documented  
 441 [Guza *et al.*, 1984; Tissier *et al.*, 2015; Inch *et al.*, 2017].



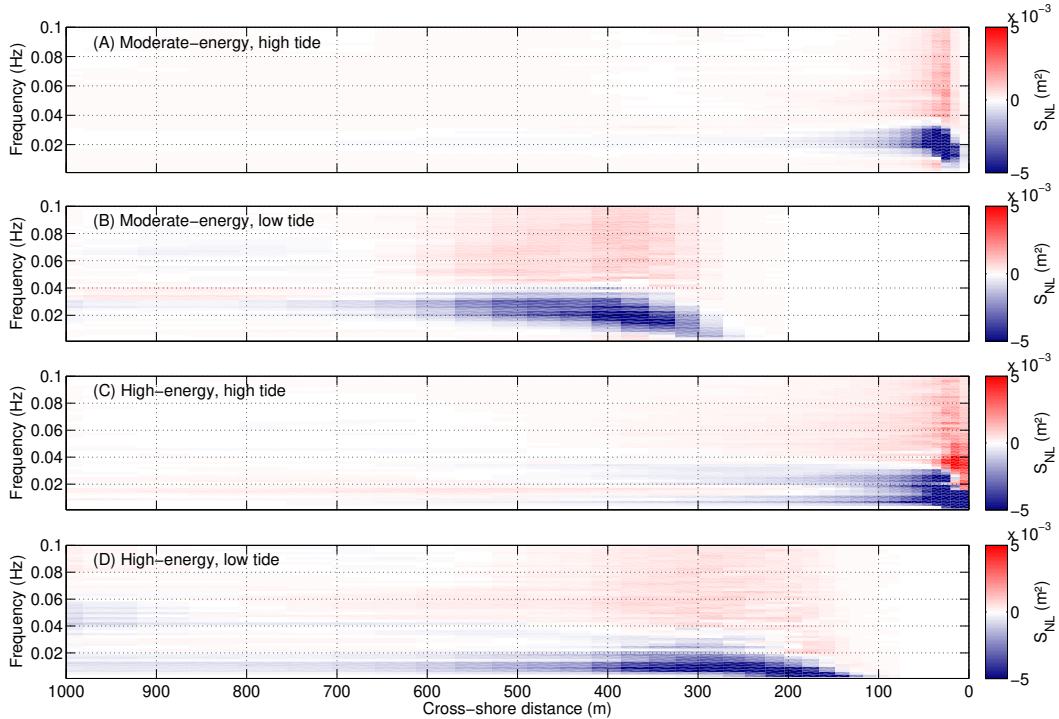
442 **Figure 10.** (A) Modeled correlation coefficient between the WEE and incoming IG waves and  
 443 (B) modeled normalized phase lag, shifted by  $\pi$  (i.e. phase lag in radians shifted by  $\pi$  and  
 444 then normalized by  $\pi$ ) between incoming IG waves and the WEE. The black solid lines correspond to  
 445 isolines of the mean water depth.

446 For storm wave conditions, a phase lag of about  $\pi/10$  is already present by 10 m water  
 447 depth (i.e. 3000 m from the shoreline, Figure 10) and increases up to  $\pi/5$  at the beginning of

448 the inner surf zone. According to *Van Dongeren et al. [2007]*, this phase lag enhances energy  
 449 transfers from the short waves to the IG waves. Due to the gentle slope of the studied beach,  
 450 this process is active over several kilometers under storm waves, which would explain the  
 451 development of such large IG waves. However, our field dataset entails several limitations  
 452 that prevent from verifying these values. First, the ADCP1 was located more than 3000 m  
 453 from the intertidal profile, which implies travel times of IG waves ranging from 400 to 500 s,  
 454 depending on the tidal phase. Over such a long distance/duration, IG waves suffer multiple  
 455 transformations (see next sections) so that we were unable to correlate the offshore WEE  
 456 with the IG waves at the intertidal sensors. Second, the width of the surf zone ranged from  
 457 200 m to more than 3000 m, so that the intertidal sensors were always located inside the surf  
 458 zone, where the correlation between IG waves and the WEE is biased positively as explained  
 459 above.

## 460 6.2 Energy transfers

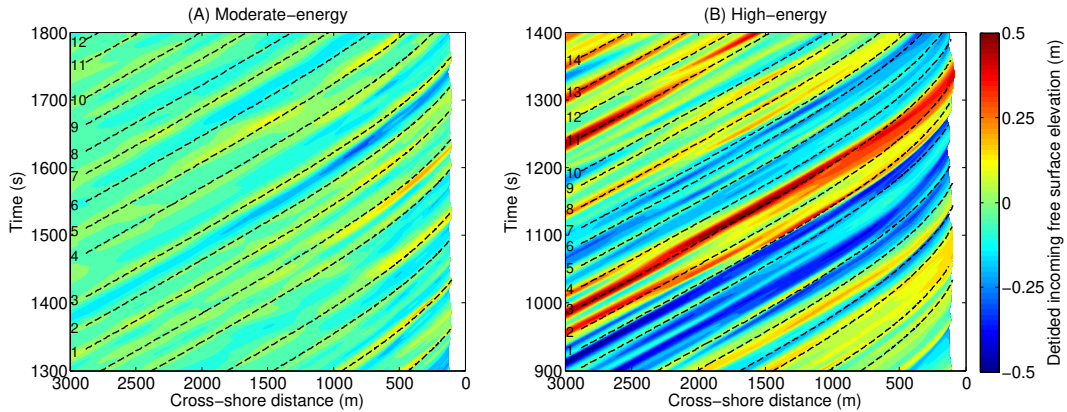
461 In order to better explain the spatio-temporal repartition of IG wave energy, source  
 462 terms for nonlinear energy transfers between IG wave frequencies  $S_{nl}$  were computed using  
 463 bispectra following *Herbers et al. [2000]* based on 24 h-long runs corresponding to moderate-  
 464 energy and storm conditions, both at low and high tide (Figure 11). This figure reveals  
 465 that, at high tide, substantial energy transfers from frequencies in the range 0.01-0.03 Hz  
 466 towards higher frequencies start to occur about 200 m from the shoreline (Figure 11-A). At  
 467 low tide, similar energy transfers occur but starting about 500 m from the waterline (Figure  
 468 11-B). Surprisingly, the overall patterns of energy transfers are not very different for storm  
 469 conditions, except that they affect lower IG wave frequencies (0.002 Hz to 0.02 Hz) (Figure  
 470 11-C and -D). Note that for these high-energy cases, the overall patterns are shifted onshore  
 471 because the mean water level is higher due to a larger wave setup.



472 **Figure 11.** Source terms for nonlinear energy transfers between IG wave frequencies along the  
 473 studied cross-shore profile computed for each frequency following *Herbers et al. [2000]* over 24 h  
 474 stationary runs for moderate and high-energy conditions, both at low and high tide.



475 For moderate-energy wave conditions, the cross-shore evolution of  $S_{nl}$  (Figure 11-A  
 476 and -B) suggests that the decrease in mean incoming IG wave period  $T_{m02,IG^+}$  with the  
 477 water depth (Figure 7) and its subsequent tidal modulation is explained by energy transfers  
 478 from principal components to higher harmonics via non-linear coupling between triads. In  
 479 shallow depth (i.e. less than 1 m), the increase in  $T_{m02,IG^+}$  is explained by the breaking  
 480 of the higher-frequency IG waves, a process well supported at gently-sloping beaches by  
 481 field observations [De Bakker et al., 2014; Inch et al., 2017], laboratory experiments [Battjes  
 482 et al., 2004; Van Dongeren et al., 2007; Padilla and Alsina, 2017] and numerical modelling  
 483 [Ruju et al., 2012; De Bakker et al., 2016b; Mendes et al., 2018]. For storm wave conditions,  
 484 a different situation occurs, where  $T_{m02,IG^+}$  continuously increases across the surf zone, so  
 485 that  $T_{m02,IG^+}$  almost doubles from 10 m water depth to the shoreline (Figure 7). While  
 486 the increase in  $T_{m02,IG^+}$  close to the shoreline can also be attributed to the breaking of  
 487 the highest frequency IG waves, an additional mechanism should be active in intermediate  
 488 water depths where IG waves cannot break. Indeed, classical interactions between pairs of  
 489 frequencies could hardly explain this behaviour as the computation of  $S_{nl}$  reveals virtually  
 490 no energy transfers towards very low frequencies, as for moderate-energy conditions (Figure  
 491 11). Analyzing field observations collected under storm waves at a steep rocky shore in  
 492 western Brittany, Sheremet et al. [2014] reported the development of 300 s period IG waves  
 493 along the shore. These authors applied a phase-resolving triad numerical model, which failed  
 494 to reproduce such low frequency IG waves and concluded that, as in the present study, it  
 495 does not result from classical non-linear triad interactions.



496 **Figure 12.** Timestack sample of modeled incident surface elevation ( $\eta_{IG^+}$ ) along the studied  
 497 cross-shore transect around high tide for (A) moderate incident energy and (B) high-energy (storm  
 498 Kurt). Numbers correspond to IG wave crests and the dashed black lines correspond to the troughs  
 499 of the WEE, automatically detected at  $x = 3000$  m and then computed across the surf zone.

500 While the development of IG wave super-harmonics at gently-sloping beaches is reason-  
 501 ably well documented in the literature and explained through IG-IG nonlinear interactions  
 502 [Elgar and Guza, 1985; De Bakker et al., 2015, 2016b; Inch et al., 2017; Padilla and Alsina,  
 503 2017], the transfer of energy towards subharmonic frequencies received much less attention  
 504 [De Bakker et al., 2016b]. To further look into this phenomenon, we analyzed timestack  
 505 samples of modeled incoming free surface elevation, close to high tide under moderate en-  
 506 ergy (first tidal cycle) and storm waves (fourth tidal cycle, storm Kurt) (Figure 12-A and  
 507 -B). On this figure, the troughs of the WEE were automatically detected at  $x = 3000$  m and  
 508 their location was then computed across the surf zone using the wave group velocity  $C_g$ ,  
 509 given by the linear wave theory and the representative frequency used in XBeach, which  
 510 corresponds to  $1/T_{m-1,0}$ . For moderate energy, Figure 12-A shows that IG wave crests 1  
 511 to 12 follow the WEE troughs, which means that they propagate at  $C_g$  and shows that



they are bound to the wave groups. This behaviour illustrates the dominance of the bound wave mechanism in IG wave generation, as explained in section 6.1. This situation strongly contrasts with storm wave conditions, where IG wave crests depart from the WEE troughs at different locations across the surf zone, meaning that they no longer travel at  $C_g$  but behave as free waves (Figure 12-B). For instance, focusing on the IG wave crests number 1 to 4, crest 1 seems bound to the wave group until  $x = 500$  m, crest 2 and 4 until  $x = 2300$  m and crest 3 until  $x = 1000$  m. Although less impressive, this process can also be observed for IG wave crests 6 and 10. Considering a mean water depth of 12 m at  $x = 3000$  m and a representative frequency of 0.064 Hz at the time of Figure 12-B, bound IG waves propagate at  $C_g = 9.8 \text{ m.s}^{-1}$  while free IG waves propagate at  $10.84 \text{ m.s}^{-1}$ . Whereas such differences only represent 11 % and further less when approaching the coastline, they result in travel-time differences ranging from 25 to 30 s once integrated over such a large surf zone. This allows the merging of individual crests into longer-period IG waves close to shore, as for instance crest 2 with crest 1 and crests 4 with crest 3 (Figure 12-B). A closer look at the model results however suggests that the behaviour of the near-shore IG wave-field is more complex. For instance, new IG wave crests appear inside the surf zone, such as between crests number 2 and 3 at  $x = 1500$  m or between crests 11 and 12 at  $x = 2300$  m. As these IG wave crests coincide with the crests of the WEE, they may correspond to free IG waves generated through the breakpoint mechanism [Symonds *et al.*, 1982]. This hypothesis is supported by Figure 9-C, which shows that the breakpoint mechanism is active 2000 m from the shoreline under storm waves. Future studies based on extensive field measurements and/or phase resolving models will have to investigate the detailed processes responsible for IG wave merging and the possible contribution of breakpoint-generated free IG waves.

Small beach slopes and resulting wide surf zones exacerbate this process as it provides individual IG waves with more time to travel at slightly different speed and catch up with one another. Although it could not be evidenced here, a modulation of individual IG wave celerity by longer IG waves might also be possible in this region of the shoreface [Tissier *et al.*, 2015], which would also promote the merging of individual waves. Ultimately, we propose that the interactions of incident bound and free IG waves along the gently sloping shoreface of Oléron Island explain the increase of the incoming IG wave period by a factor of two across the surf zone under storm waves (Figure 7). This mechanism also suggests that the frequency of IG waves close to shore is not only controlled by the shape of the incident short wave spectra [i.e. Hasselmann, 1962] but also by the width of the surf zone and hence the slope of the beach. This mechanism will have to be verified in the field, although instrumenting a surf zone several kilometre-wide is very challenging.

### 6.3 Implications for other studies

In this study, we observed reflexion coefficient  $R^2$  to be very high for a dissipative beach. For instance, De Bakker *et al.* [2014] and Inch *et al.* [2017] reported values for  $R^2$  of the order of 0.5 or below for beaches of comparable mean bottom slope. The presence of a steeper upper beach in Saint Trojan can explain the higher reflexion observed at high tide, but not at low tide under storm wave conditions, where  $R^2$  hardly drops below 0.5. We propose that the high reflection that we observe under storm waves is related to energy transfers towards subharmonic frequencies (section 6.2), so that the resulting 200 to 300 s period IG waves are too long to suffer a substantial dissipation, even when propagating over a mild slope. Albeit not addressing the underlying mechanisms, a few other studies reported the development of IG waves with frequencies around 0.005 Hz under storm waves and suggested that they had a key role in runup [Sheremet *et al.*, 2014; Ruggiero *et al.*, 2004]. Indeed, such low frequency IG waves suffer less dissipation when propagating in shallow depth and may therefore propagate farther inland and induce larger damages in low-lying coastal zones compared to higher-frequency IG waves. The generation of low-frequency IG waves through merging of bound and free waves across wide surf zones appears therefore as a process of key importance and will have to be investigated at other sites, such as the very gently sloping coastlines of Bangladesh, which are extremely vulnerable to flooding under tropical

565 hurricanes [*Krien et al.*, 2017]. This process should also be investigated at large estuaries  
566 and tidal inlets, where the ebb deltas can drive the development of kilometer-wide surf zones.  
567

568 Besides, it is nowadays well admitted that free IG waves in the ocean are the main  
569 source of background-free oscillations of the solid earth, also referred to as "the hum of  
570 the Earth" [e.g. *Rhie and Romanowicz*, 2006; *Webb*, 2007]. As better understanding the  
571 generation of the hum could help refining the use of microseism background signals to  
572 investigate the structure of the solid Earth, understanding IG wave reflection along the  
573 coast is of key importance. Correlating deep ocean pressure measurements with short-wave  
574 bulk parameters over the North Atlantic Ocean, *Crawford et al.* [2015] proposed that the  
575 main source for free IG wave generation was located between the Western part of the Iberic  
576 Peninsula and NW Africa, namely because they display steep beaches. Our study suggests  
577 that strong reflection can also occur along dissipative beaches under storm waves, which  
578 will have to be considered in future studies on deep ocean IG waves.

## 579 7 Conclusions

580 This study aimed at improving our understanding of the generation and transfor-  
581 mation of IG waves, combining an unpublished data set with numerical modeling. The  
582 development of exceptionally large IG waves was primarily explained by very energetic and  
583 narrow-banded incident short waves associated with the storm Kurt. The analysis of model  
584 results revealed that the bound wave mechanism was clearly dominant over the breakpoint  
585 mechanisms in the generation of IG waves. Model results also showed that the gently sloping  
586 shoreface of the study area leads to the presence of a phase lag between IG waves and WEE  
587 over several kilometers under storm waves, which certainly enhanced IG wave generation  
588 through a dynamic shoaling, although our dataset did not allow to further analyze this  
589 process. The XBeach modelling system was found capable of reproducing the generation  
590 and transformation of such IG waves, which is an important result as XBeach is becoming  
591 more and more popular while detailed hydrodynamic validations are lacking under storm  
592 conditions. Model results and field observations revealed that large energy transfers occur  
593 in the IG band across the surf zone, with the development of superharmonics but also the  
594 transfers of energy towards subharmonic frequencies. While the former behaviour is reason-  
595 ably well documented in the literature and explained by non-linear coupling between triads,  
596 the latter was reported in a few studies only and we propose that it is (at least partly)  
597 related to the merging of IG waves across the surf zone. According to our modelling results,  
598 IG wave merging seems to be related to the combination of free and bound IG waves in the  
599 surf zone, traveling at different celerities over a long distance. This mechanism will have to  
600 be verified on the field and is potentially of key importance under extreme storms, because  
601 low-frequency IG waves suffer little dissipation and may therefore propagate farther inland  
602 and induce larger damages compared to higher frequency IG waves. This mechanism also  
603 results in IG-wave reflection surprisingly high for a dissipative beach, which has implications  
604 for future studies on deep ocean IG waves.

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611 making the code available. The processed field data and model input files required to run  
612 the XBeach simulations presented in this paper are available through a Zenodo repository  
613 (DOI:10.5281/zenodo.3753018).

614

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