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1 **Non-hydrostatic, non-linear processes in the surf zone**

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4 **Key Points:**

- 5 • Sub-surface pressure and lidar data are used to study the non-linear and non-
- 6 hydrostatic character of surf zone waves
- 7 • Non-hydrostatic effects are strong even in the inner surf zone, where broken
- 8 waves are sharp-crested and have a steep front
- 9 • Oscillatory flow under broken waves is dominated by irrotational motions

## Abstract

In the surf zone, non-hydrostatic processes are either neglected or estimated using linear wave theory. The recent development of technologies capable of directly measuring the free surface elevation, such as 2D lidar scanners, allow for a thorough assessment of the validity of such hypotheses. In this study, we use sub-surface pressure and lidar data to study the non-linear and non-hydrostatic character of surf zone waves. Non-hydrostatic effects are found important everywhere in the surf zone (from the outer to the inner surf zones). Surface elevation variance, skewness and asymmetry estimated from the hydrostatic reconstruction are found to significantly underestimate the values obtained from the lidar data. At the wave-by-wave scale, this is explained by the underestimation of the wave crest maximal elevations, even in the inner surf zone, where the wave profile around the broken wave face is smoothed. The classic transfer function based on linear wave theory brings only marginal improvements in this regard, compared to the hydrostatic reconstruction. A recently developed non-linear weakly dispersive reconstruction is found to consistently outperform the hydrostatic or classic transfer function reconstructions over the entire surf zone, with relative errors on the surface elevation variance and skewness around 5% on average. In both the outer and inner surf zones, this method correctly reproduces the steep front of breaking and broken waves, and their individual wave height to within 10%. The performance of this irrotational method supports the hypothesis that the flow under broken waves is dominated by irrotational motions.

## Plain Language Summary

In the surf zone, waves undergo rapid changes in shape, passing from steep and skewed waves right before breaking to sawtooth-shaped asymmetric bores. Capturing and understanding these changes is crucial for coastal researchers and engineers since the breaking wave-induced hydrodynamics shape beaches at various temporal and spatial scales. In this study, we use lidar scanners and pressure sensors to study the non-hydrostatic and non-linear character of surf zone waves. We show that non-hydrostatic effects remain strong over the entire surf zone, i.e. fluid accelerations are important and the hypothesis of a hydrostatic pressure field leads to large deviations of the real surface elevation. More specifically, wave crests elevation are underestimated, and the sharp-crested shape of broken waves is rounded-off. A recently developed non-linear weakly dispersive method to reconstruct the free surface from sub-surface pressure is found to consistently outperform the hydrostatic or classic transfer function reconstructions over the entire surf zone, with relative errors on the surface elevation variance (related to the wave energy) and skewness (related to wave shape) around 5% on average. The performance of this irrotational method supports the hypothesis that the flow under broken waves is dominated by irrotational motions.

## 1 Introduction

In the surf zone, waves undergo rapid changes in shape, passing from steep and skewed waves right before breaking to sawtooth-shaped asymmetric bores in what is referred to as the inner surf zone (e.g., Basco, 1985; Battjes, 1988). Most of the energy dissipated during breaking processes is transferred to the water column through mixing (Ting and Kirby, 1996; Drazen and Melville, 2009), induces a wave setup near the shoreline (e.g., Longuet-Higgins and Stewart, 1964; Stive and Wind, 1982; Apotsos et al., 2007; Guérin et al., 2018) and forces the circulation of the nearshore (e.g., see Svendsen, 1984; Deigaard et al., 1991; Peregrine and Bokhove, 1998; Feddersen et al., 1998; Bühler and Jacobson, 2001; Bonneton et al., 2010; Castelle et al., 2016). Wave-induced nearshore circulation shape beaches at various temporal and spatial scales (Wright and Short, 1984) and are also important for cross-shelf exchanges of sediment, pollutants and nutrients (e.g., Shanks et al., 2010). In addition, wave orbital velocity skewness and asymmetry, which result from wave shape changes in the nearshore, drive a net onshore sediment transport (Hoefel and Elgar, 2003) and are therefore key to pattern and rate of beach recovery after storms. Measuring accurately the complex changes that waves exhibit around and after the breaking point is thus critical to coastal engineers and researchers.

The problem of measuring waves can be simply viewed as our capacity to detect the air/water interface along with its spatial and temporal evolution. The surf zone is characterized by turbulent flows where breaking waves entrain large volumes of air in the water column, so that, at almost every stage of the wave propagation (under the wave front, crest and trough), air bubbles can be found at various concentrations near and under the free surface (Cox and Shin, 2003; Mori et al., 2007; Kimmoun and Branger, 2007). Directly measuring the free surface of breaking waves in the field is thus a challenging task, and seminal studies on surf zone wave kinematics mainly focused on the development of such measurement techniques (e.g., see Thornton et al., 1976). Although capacitance-type of wave gauges showed good skill in the field to measure the free surface, pressure sensors rapidly became the most commonly used approach for measuring waves in the surf zone, as they are robust and relatively cheap. However, retrieving the free surface from pressure measured at the bottom poses mathematical challenges, especially in the surf zone, where waves are highly non-linear.

The surf zone is generally divided into two regions: the outer surf zone, where waves break, and the inner surf zone, where most waves propagate as quasi-steady bores (Basco, 1985; Svendsen et al., 1978). Close to breaking, waves exhibit steep faces and, even after breaking, are characterized by strong vertical accelerations (e.g., see van Dorn, 1978; Elgar et al., 1988), which explains why non-hydrostatic effects are important in this region (see illustration in Figure 1a). In the inner surf zone, non-hydrostatic processes are generally assumed to be negligible (e.g., Raubenheimer et al., 1996; Sénéchal et al., 2001), due to the resemblance of broken waves with bores, under which the pressure field is very close to be hydrostatic (Madsen and Svendsen, 1983). Non-hydrostatic effects typically concentrate in the vicinity of the broken wave front (see illustration in Figure 1b), and have two main origins: 1) the vertical acceleration associated with the wave motion and 2) the roller structure where the flow is highly turbulent and strongly non-uniform in the vertical (e.g., see Govender et al., 2002). The numerical investigations of Lin and Liu (1998) for instance suggest that the assumption of a hydrostatic pressure field shows deviations of the free surface less than 10% under the crest of broken waves. Elsewhere (e.g. trough region), the fluid motions are near-horizontal and the hypothesis of a hydrostatic pressure field yields good estimates of the free surface elevation (Stive, 1980). Nonetheless, experimental data described in van Dorn (1978) show that 20-30% of error on the crest elevation can be expected in

100 the inner surf zone with the hydrostatic hypothesis, which is unacceptable for many  
101 coastal applications.

102 The supposedly negligible non-hydrostatic effects in the inner surf zone encour-  
103 aged researchers to use the non-linear shallow water equations (NSWE) to simulate  
104 wave propagation in the inner surf zone (Kobayashi et al., 1989; Raubenheimer et al.,  
105 1996; Bonneton, 2007). This modelling approach, where the wave front is treated as a  
106 shock, reproduces quite well the non-linear distortion associated with saw-tooth waves  
107 in the surf zone, their celerity and the energy dissipation related to breaking processes  
108 (Bonneton, 2007). These encouraging results lead researchers to implement such hy-  
109 drostatic shock-wave method in fully non-linear, non-hydrostatic models in order to  
110 deal with breaking and broken waves (e.g., Bonneton et al., 2011; Tissier et al., 2012;  
111 Shi et al., 2012; Smit et al., 2013). If these models provide a correct description of the  
112 global wave evolution, from the shoaling to the swash zone, their ability to properly  
113 reproduce non-hydrostatic wave processes in the entire surf zone remains questionable.

114 Early field studies also focused on the capacity of linear wave theory to correct for  
115 the depth-attenuation of the pressure signal and retrieve free surface and wave statistics  
116 elsewhere in the surf zone and in deeper water (e.g., Guza and Thornton, 1980; Thor-  
117 nton and Guza, 1983). Although wave-by-wave analyses were clearly not recommended  
118 (Bishop and Donelan, 1987), linear wave theory became the most common approach  
119 to reconstruct the free surface and retrieve wave characteristics from bottom-mounted  
120 pressure sensors (e.g., Sallenger Jr. and Holman, 1985; Elgar et al., 1997; Ruessink,  
121 2010, and many others). Due to the need for cutoff frequencies, this approach does  
122 not allow spectral analyses to be performed at frequencies higher than approximately  
123 3 to 4 times the peak frequency (typically  $f < 0.3$  Hz), meaning that high harmonics,  
124 which reflect the degree of non-linearities, are not considered. The recent develop-  
125 ment of techniques capable of directly measuring the free surface based on acoustic  
126 (Bonneton et al., 2018; Mouragues et al., 2019) or lidar technology (Martins et al.,  
127 2017a) highlighted the limits of linear wave theory, which strongly underestimates the  
128 non-hydrostatic character of shoaling and breaking waves. This has implications in  
129 the estimates of surface elevation second (variance) and third-order (skewness and  
130 asymmetry) parameters as well as elevation extrema and distributions.

131 The present study has two main objectives: 1) Quantify the non-hydrostatic pro-  
132 cesses throughout the entire surf zone and 2) Apply the recently developed non-linear  
133 weakly dispersive reconstruction method of Bonneton et al. (2018) in the surf zone.  
134 We use sub-surface pressure data and direct measurements of the surface elevation  
135 obtained by lidar scanners previously collected in the field. The paper is organized as  
136 follows. In Section 2, we first briefly review the different field measuring techniques  
137 adapted to the surf zone. The three methods used in this paper to reconstruct the free  
138 surface from sub-surface pressure measurements (hydrostatic, linear and non-linear  
139 weakly dispersive) are also recalled. The different datasets collected at the macroti-  
140 dal, dissipative site of Saltburn-by-the-Sea, UK, are presented in Section 3. In Section  
141 4, we analyze the non-hydrostatic character of surf zone waves, in relation to their  
142 relative position in the surf zone (outer to inner surf zone). This is done by comparing  
143 surface elevation statistics (percentiles, second and third-order parameters) computed  
144 on the hydrostatic reconstruction with the direct measurements obtained from lidars.  
145 The three reconstruction methods considered here are then compared and their per-  
146 formances are analyzed in Section 5, in both the frequency and temporal domains.  
147 Finally, we summarize the different findings of this study in Section 6.

## 2 In situ methods for characterizing non-hydrostatic wave processes in the surf zone

### 2.1 Direct measurements of surf zone waves

Past field studies analyzed the cross-shore transformation of surf zone waves using visual estimates of the free surface obtained from a combination of video cameras and photopoles (Mizuguchi, 1982; Ebersole and Hughes, 1987). The presence of splashes around the poles (Ibaceta et al., 2018) and the errors associated with the pixel resolution limit the accuracy of the measurements to several centimeters in the surf zone. Although generally used in laboratory conditions (e.g., see Flick et al., 1981), capacitance and resistive types of wave gauges were used very early in the field to estimate surface elevation spectra in the shoaling region (Tucker and Charnock, 1954; Simpson, 1969; Flick et al., 1979) and in the surf zone (e.g., Thornton et al., 1976; Gonalo, 1978; Thornton and Guza, 1983). More information on this type of gauges can be found in Flick et al. (1979), Shand et al. (2009) and the references therein. When calibrated, these gauges allow  $O(\text{mm})$  accuracy in controlled environments, however, the presence of large pockets or fractions of air under breaking waves potentially leads to large errors in the estimation of the free surface, or at least its envelop. For instance, Kimmoun and Branger (2007) compared measurements from resistive gauges and PIV techniques, showing an underestimation of the surface elevation by the resistive gauges of up to 60% in the plunging and splash-up region, while the differences lied between 20 and 30% in the inner surf zone. This is explained by the working principle of resistive wave gauges whose response is proportional to the wire wet length. This cross-comparison between measuring techniques near the breaking point underlines the importance to consistently compare the same quantities, whether the comparisons are made between different measuring techniques or between numerical models and experimental data (e.g., see Lowe et al., 2019).

Acoustics sensors provide another method to detect the free surface, based on the time of flight technique. These can be deployed at the bottom of the water column (Pedersen et al., 2002; Birch et al., 2004; Mouragues et al., 2019) or above the surface (Turner et al., 2008), although the latter study focuses on the swash zone. When the air fraction along the water column is very small (i.e. no wave breaking), sub-surface acoustic sensors give very accurate estimates of the free surface elevation (e.g., see the comparisons with direct measurements from lidar scanners in Martins et al., 2017b). The presence of air bubbles associated with wave breaking processes prevents sound waves to reach the surface, hence making this method inappropriate for surf zone applications (Birch et al., 2004). In this case, bottom-mounted acoustic sensors would typically measure the lower bound of the surface roller structure (see illustration in Figure 1) or air pockets, which can be used in order to characterize breaking wave-induced air plumes in large scale experiments (Bryan et al., 2019).

As mentioned above, lidar scanners (mostly in the infrared spectrum) are capable of directly measuring the free surface, and are thus very powerful tools to study surf zone waves. The scanners can be stationed near the shoreline (Brodie et al., 2015; O’Dea et al., 2019) or mounted on structures such as temporary towers (Martins et al., 2016) or jetties (Martins et al., 2017c; Harry et al., 2018). 2D lidars provide highly-resolved, direct measurements of wave profiles which, as opposed to single-point sensors, allow the determination of geometric information about the wave shape, and its cross-shore evolution (e.g., on the roller angle and length, see Martins et al., 2018). Contrary to capacitance or resistive type of wave gauges, which can only underestimate the free surface elevation due to the presence of air fraction, lidar scanners provide the surface elevation envelope. Note that the application of lidars is not limited to the field since they can also be used during small (Blenkinsopp et al., 2012) and large scale (Vousdoukas et al., 2014; Martins et al., 2017a) laboratory experiments. Finally, few studies used photogrammetry techniques and data from colocated video cameras

to reconstruct the sea surface elevation and gain new insights into the directional properties of wave spectra in relatively deep water (Benetazzo, 2006; Peureux et al., 2018). Although these techniques show great promises, especially in terms of spatial resolution and coverage, its application to nearshore, breaking waves remains scarce (de Vries et al., 2011; Filipot et al., 2019), which is likely due to the experimental set-up and the data processing procedures that entail many technical complications (e.g. time synchronization).

## 2.2 Sub-surface pressure measurements of surf zone waves

Pressure sensors have always represented a cheap and robust solution to measure water waves in the nearshore, with studies dating back to the 40s (Folsom, 1947; Seiwel, 1947). However, as mentioned earlier, reconstructing the free surface from pressure measured is challenging, especially under strongly non-linear waves such as in the surf zone. The recent development of remote sensing methods capable of directly measuring surf zone waves is not only explained by technological advances, but is also motivated by the need to obtain reliable and accurate measurements where pressure sensors and the classic surface reconstruction methods fail. Mouragues et al. (2019) give a recent review on the different methods to reconstruct the free surface from sub-surface pressure measurements, with an application to shoaling waves. Below, we recall the three most commonly used methods for practical nearshore applications: the hydrostatic reconstruction ('hyd'), the classic transfer function method (based on linear wave theory, 'lin') and the non-linear weakly dispersive reconstruction method ('snl') recently derived in Bonneton et al. (2018).

The main hypothesis used to derive the linear and non-linear weakly dispersive formula is that the flow is irrotational. Here, it is important to note that these two methods correct the non-hydrostatic effects associated with the irrotational part of the wave flow. Hence, none of these methods are designed to estimate the non-hydrostatic effects related to the roller, which is the aerated and turbulent structure located at the broken wave face (Figure 1). For more information on their derivation, the reader is referred to Bonneton and Lannes (2017), Bonneton et al. (2018) and Mouragues et al. (2019).

### *Hydrostatic reconstruction.*

Neglecting the vertical acceleration in the momentum equation yields the hydrostatic reconstruction of the free surface:

$$\zeta_{\text{hyd}} = \frac{P_m - P_{\text{atm}}}{\rho g} + \delta_m - h_0, \quad (1)$$

where  $P_m$  is the pressure measured at a distance  $\delta_m$  from the bed,  $P_{\text{atm}}$  is the atmospheric pressure,  $\rho$  is the water density,  $g$  is the gravity constant and  $h_0$  is the mean water depth. Note that the different variables used throughout the paper are listed in Table 1.

The hypothesis of a hydrostatic pressure field gives good estimate of the free surface elevation for very long waves such as tidal waves, which are characterized by a very small dispersion (or shallowness) parameter  $\mu$  (with  $\mu = kh_0$ , where  $h_0$  is the mean water depth and  $k$  is the wave number). Note that contrary to Bonneton and Lannes (2017), Bonneton et al. (2018) and Mouragues et al. (2019), we choose, for the sake of readability, to define  $\mu$  without the power 2. In opposite to long waves, short waves propagating in the nearshore exhibit rather steep faces, characterized by strong fluid accelerations. Hence, large errors on the reconstructed surface are expected in the shoaling and surf zones, especially close to the breaking point (e.g., see van Dorn, 1978).

### *Classic transfer function method.*

247 The classic transfer method uses linear wave theory to approximate the velocity  
248 potential time derivative (e.g., see Bishop and Donelan, 1987). This can be written:

$$\mathcal{F}\{\zeta_{\text{lin}}\}(\omega) = K_{p,\text{lin}}(\omega)\mathcal{F}\{\zeta_{\text{hyd}}\}(\omega) \quad (2)$$

$$K_{p,\text{lin}}(\omega) = \frac{\cosh(kh_0)}{\cosh(k\delta_m)} \quad (3)$$

$$\omega^2 = gk \tanh(kh_0), \quad (4)$$

249 where  $\omega$  is the radial frequency and  $\mathcal{F}\{\cdot\}$  is the Fourier transform. Eq. 4 corresponds to  
250 the dispersion relation given by linear wave theory, and is used in Eq. 3 to compute the  
251 correction factor applied to the hydrostatic reconstruction in Eq. 2 (in the frequency  
252 space). Reconstructing the surface elevation using the transfer function method given  
253 by linear wave theory (Eq. 2-4) yields good estimates of bulk parameters for linear  
254 waves (e.g., Homma et al., 1966; Esteva and Harris, 1970; Grace, 1978; Cavaleri, 1980,  
255 and many others) as long as adequate deployment procedures and analyses techniques  
256 are used (Bishop and Donelan, 1987).

257 As wave non-linearities increase in shallow depths, the classic transfer function  
258 written in Eq. 2 needs a cutoff frequency in order to avoid the overestimation of the  
259 correction factor  $K_p$  at relatively high frequencies (e.g.,  $f > 0.4f_p$ , with  $f_p$  the peak  
260 frequency), see for instance Gonçalo (1978) and Mouragues et al. (2019). This overesti-  
261 mation was generally attributed to the presence of noise in the pressure measurements  
262 (e.g., Guza and Thornton, 1980; Jones and Monismith, 2007, and many others). Bon-  
263 neton and Lannes (2017) and Bonneton et al. (2018) show that the reason why the  
264 transfer function from linear wave theory blows up is in fact due to wave non-linearities  
265 and the presence of secondary harmonics. These harmonics are phase-locked (bound)  
266 to the primary wave and their wave number is thus largely overestimated when using  
267 the dispersion relation from linear wave theory given in Eq. 4 (see Bonneton and  
268 Lannes, 2017). This is supported by the analyses from Lee and Wang (1984) and  
269 the recent application of the non-linear weakly dispersive formula by Mouragues et al.  
270 (2019). The need for a cutoff frequency prevents the accurate description of high har-  
271 monics, meaning that sharp-crested waves cannot be accurately described and their  
272 wave height and skewness are generally largely underestimated (e.g., Martins et al.,  
273 2017a; Bonneton et al., 2018; Mouragues et al., 2019).

#### 274 *Non-linear weakly dispersive reconstruction.*

Bonneton and Lannes (2017) presented a fully-dispersive non-linear reconstruc-  
tion method that yields better description of second and third-order moments of fully-  
dispersive wave groups compared to linear wave theory or other non-linear reconstruc-  
tions such as the heuristic method by Vasani and Oliveras (2017). Building on this  
work, Bonneton et al. (2018) derived a non-linear formula for weakly dispersive waves  
( $\mu^2 \lesssim 0.3$ ) which reads:

$$\zeta_{\text{sl}} = \zeta_{\text{hyd}} - \frac{h_0}{2g}(1 - (\delta_m/h_0)^2) \frac{\partial^2 \zeta_{\text{hyd}}}{\partial t^2} \quad (5)$$

$$\zeta_{\text{snl}} = \zeta_{\text{sl}} - \frac{1}{g} \left( \frac{\partial}{\partial t} \left( \zeta_{\text{sl}} \frac{\partial \zeta_{\text{sl}}}{\partial t} \right) - (\delta_m/h_0)^2 \left( \frac{\partial \zeta_{\text{sl}}}{\partial t} \right)^2 \right) \quad (6)$$

275 where  $\zeta_{\text{sl}}$  is a linear shallow water reconstruction upon which the non-linear recon-  
276 struction  $\zeta_{\text{snl}}$  is based. Unlike the transfer function method (Eq. 2), the non-linear  
277 formula of Eq. 6 does not use the dispersion relation, meaning that the cutoff fre-  
278 quency can be much higher (Bonneton et al., 2018; Mouragues et al., 2019). This  
279 implies that the shape of non-linear waves propagating in the shoaling region or near  
280 the breaking point can be better described. Similarly, free surface high-order moments  
281 are also more accurately estimated in these regions (Bonneton et al., 2018; Mouragues  
282 et al., 2019).



283 The fact that the non-linear formula (Eq. 6) uses and corrects a linear recon-  
 284 struction (Eq. 5) explains why the non-linear reconstruction can still be sensitive to  
 285 wave non-linearities and might require a cutoff frequency smaller than the frequency  
 286 where noise dominates in the pressure data. This point is of relevance for coastal appli-  
 287 cations, and will be further discussed in Section 5 and in the Appendix for the present  
 288 application in the surf zone. Finally, it is worth noting that the time-averaged surface  
 289 elevation predicted by the non-linear reconstruction method is similar to that of the  
 290 hydrostatic reconstruction, i.e.  $\langle \zeta_{\text{snl}} \rangle = \langle \zeta_{\text{hyd}} \rangle$  (with  $\langle \cdot \rangle$  the time-averaging operator).

### 291 3 Methods

#### 292 3.1 Study site and field data

293 The present study uses lidar and pressure data collected during the field experi-  
 294 ments performed at Saltburn-by-the-Sea, UK (Figure 2a) during April 2016 (Martins  
 295 et al., 2017c, 2018). Similar to Martins et al. (2017c, 2018), we only use data from  
 296 9-10 April 2016, corresponding to a swell event characterized by a peak wave period  
 297  $T_p = 9 - 11$  s and a significant wave height  $H_s = 1$  m. During these two days, a mean  
 298 peak wave direction of  $16.9^\circ$  NE was measured at the nearshore buoy deployed in 17-m  
 299 depth, with a directional spread of  $15.3^\circ$ . Since the coastline around the pier is ori-  
 300 ented towards  $18^\circ$  NE, incident waves were essentially propagating shore normal and  
 301 parallel to the pier. The Saltburn beach is dissipative ( $\tan \beta \sim 1 : 65$ ) and presents  
 302 a macrotidal regime, with a mean tidal range of 5.2 m measured at the Whitby tidal  
 303 gauge during the period of interest, see Figure 2a for location.

304 During these experiments, three eye-safe 2-D lidar scanners (SICK LMS511,  $\lambda =$   
 305 904 nm) were deployed along the pier to measure the time-varying free surface elevation  
 306 of shoaling, breaking and broken waves at 25 Hz (Figures 2b and 2c). Three Nortek  
 307 Acoustic Doppler Velocimeters (ADVs) were deployed at three distinct cross-shore  
 308 locations (Figure 2c) to measure current velocities several centimeters ( $\sim 10$  cm)  
 309 above the seabed. Near-bed pressure was measured at these locations by three pressure  
 310 transducers (PT) deployed vertically and synchronized with the ADVs. The most  
 311 seaward and the middle PTs corresponded to external GE Druck PTX1830 sensors,  
 312 while the most landward PT corresponded to the internal pressure sensor from the  
 313 third ADV. Both pressure and current data were collected at 16 Hz. Although the  
 314 beach experienced very little morphological change throughout the experiment, the  
 315 distance between the pressure sensor and the bed level was measured at every low  
 316 tide for surface reconstruction purposes. Similarly, the ADVs' head position were  
 317 monitored, and if needed, were repositioned to maintain the  $\sim 10$ -cm distance above  
 318 the seabed. Finally, an additional pressure transducer was deployed at the seaward  
 319 limit of the pier in order to measure local wave conditions outside the surf zone. The  
 320 data from this PT was also used to estimate the peak period, later used to compute  
 321 the local wave number  $k$  with the linear dispersion relation (Eq. 4).

#### 322 3.2 Data processing

323 Time series of pressure and surface elevation directly measured by the lidar were  
 324 organized in bursts of 512 s. The lidar data was first re-sampled at 16 Hz to match the  
 325 pressure time frame. Each of the burst time series were linearly detrended to remove  
 326 the tidal component. Note that this is the only signal processing that was applied to  
 327 the time series as no low/high-pass filters were used.

328 As noted above, two of the pressure transducers were external sensors, designed  
 329 to work in shallow environments (maximum depth of 10 m) while the internal pressure  
 330 sensor from the most landward ADV was designed to work in deeper water (100-m  
 331 depth). This is an important detail as much higher noise was present in the measure-

332 ments from the Nortek PT, which prevented the analysis of the pressure time series  
 333 at high frequencies. Hence, the data from that particular PT was disregarded. Bursts  
 334 where the lidar data had more than 10% non-return signal (before re-sampling) were  
 335 also disregarded. This only concerned the data at the location of the middle ADV,  
 336 since it was located between two scanners. In this region, the lidar scanners need the  
 337 persistent presence of foam to return a continuous signal. On the contrary, a con-  
 338 tinuous return signal was obtained by the lidar at the most seaward PT, even in the  
 339 absence of breaking events, as it is located closer to nadir.

340 As the burst data covered several hours of the tidal cycles, it is important for  
 341 the present analysis to qualitatively know in which region of the surf zone waves were  
 342 propagating. This was accomplished by visually estimating  $Q_b$ , the fraction of breaking  
 343 and broken waves at the ADV location from the lidar data. Following Martins et al.  
 344 (2017c), waves were considered breaking at the ADV location only when the first  
 345 features associated with breaking processes (e.g. splashes, active wave face) could  
 346 already be detected at that position. The results of this detection are presented in  
 347 Figure 3, in which we can observe a linear trend between  $Q_b$  and  $\langle \zeta^2 \rangle$ , the surface  
 348 elevation variance measured by the lidar. As in the surf zone, the surface elevation  
 349 variance is largely dictated by the water depth, Figure 3 also reveals the controlling  
 350 effect of the water depth on  $Q_b$ . The data points are coloured by the relative water  
 351 depth  $\mu$ , which, as a dispersive parameter, characterizes the non-hydrostatic effect.  
 352 The smallest  $\mu$  values coincide with the lowest  $\langle \zeta^2 \rangle$  values and correspond to the  
 353 boundary between the inner surf zone and the swash zone, which was dominated  
 354 by infragravity waves. The presence of small waves carried by these low-frequency  
 355 motions explain why the breaking fraction is not 1 for the lowest  $\mu$  values. The largest  
 356  $\mu$  values, which coincide with the highest  $\langle \zeta^2 \rangle$ , correspond to the boundary between  
 357 the outer surf zone and the shoaling region, where the largest waves first break. The  
 358 scatter observed in Figure 3 can be explained by the slight inter-tidal variations in  
 359 wave conditions observed during the two days considered here (Martins et al., 2017c)  
 360 as well as by the natural variation of  $Q_b$  in natural surf zones (e.g., see the recent  
 361 study of Stringari and Power, 2019).

362 In the remainder of the paper, we thus use the shallowness parameter  $\mu$  as an  
 363 indicator of the relative position in the surf zone. The non-hydrostatic and non-  
 364 linear character of the surf zone waves monitored at Saltburn are studied using second  
 365 (variance) and third-order surface elevation parameters (skewness and asymmetry). If  
 366  $\zeta(t)$  denotes the free surface elevation at one spatial location, with  $t$  the time, these  
 367 quantities can be defined as follows:

$$\begin{aligned} \text{Variance :} & \quad \langle (\zeta - \langle \zeta \rangle)^2 \rangle \\ \text{Skewness :} \quad S_k &= \frac{\langle (\zeta - \langle \zeta \rangle)^3 \rangle}{\langle (\zeta - \langle \zeta \rangle)^2 \rangle^{3/2}} \\ \text{Asymmetry :} \quad A_s &= \frac{\langle (\mathcal{H}(\zeta - \langle \zeta \rangle))^3 \rangle}{\langle (\zeta - \langle \zeta \rangle)^2 \rangle^{3/2}} \end{aligned}$$

368 where  $\mathcal{H}(\cdot)$  is the Hilbert transform. The variance of the surface elevation is associ-  
 369 ated to the wave energy, while its skewness and asymmetry characterize the vertical  
 370 (peaked) and horizontal (pitched forward) asymmetry of the wave form respectively.

#### 371 4 Non-hydrostatic wave processes in the surf zone

372 In this section, we quantify the non-hydrostatic character of surf zone waves by  
 373 comparing statistics and bulk parameters computed on the hydrostatic reconstruction  
 374 ( $\zeta_{\text{hyd}}$ , Eq. 1) with the direct measure from the lidar scanners ( $\zeta_{\text{lidar}}$ ).

#### 4.1 Bulk and high-order surface elevation parameters

We first compare the 5% and 95% percentiles  $\zeta_{5\%}$  and  $\zeta_{95\%}$  of the two surface elevation datasets.  $\zeta_{5\%}$  represents the lower 5% of the surface elevation time series for each burst, hence corresponding to wave troughs while  $\zeta_{95\%}$  represents the highest 5% of the surface elevation time series, hence corresponding to the highest wave crests of the burst. The fact that  $\zeta_{\text{lidar},5\%}$  and  $\zeta_{\text{hyd},5\%}$  follow the 1:1 line in the present dataset (Figure 4a) means that the pressure field is mostly hydrostatic around wave troughs in the entire surf zone, which is in agreement with past experimental and numerical studies (e.g., van Dorn, 1978; Stive, 1980; Lin and Liu, 1998). In contrast,  $\zeta_{\text{hyd},95\%}$  consistently underestimates  $\zeta_{\text{lidar},95\%}$  (Figure 4b): the relative differences, computed here as  $100 \times |\zeta_{\text{lidar},95\%} - \zeta_{\text{hyd},95\%}| / \zeta_{\text{lidar},95\%}$ , decrease from 15-20% in the outer surf zone to approximately 5% in the inner surf zone. This suggests that the hydrostatic reconstruction underestimates the elevation of the highest wave crests, independently from the relative position in the surf zone.

Next, we present in Figure 5a the comparison of the variance of the two surface elevation datasets for the 52 bursts analyzed here. The hydrostatic reconstruction is found to consistently underestimate the free surface elevation variance, and hence the wave energy in the surf zone. In the outer surf zone ( $\mu > 0.26$ ), the hydrostatic reconstruction underestimates the elevation variance by up to 30%; this is expected since breaking waves are characterized by rapid vertical acceleration under the crest (e.g., van Dorn, 1978; Hieu et al., 2004). For values down to  $\mu \sim 0.20$ , non-hydrostatic effects remain strong, as seen in the relatively constant underestimation of the surface elevation variance by the hydrostatic reconstruction (between 25-30%). Only in the inner surf zone, which corresponds to  $\mu < 0.16$  in the present dataset, we observe differences of approximately 10% in the elevation variance and thus less non-hydrostatic effects. It can be noted that the variation of the relative error with the non-dimensioned water depth is in qualitative agreement with the experimental data from van Dorn (1978).

Third-order parameters of  $\zeta_{\text{hyd}}$  also display large relative differences compared to the lidar data. The skewness  $S_{k,\text{hyd}}$  of the surface elevation reconstructed from the hydrostatic assumption underestimates the values obtained from the lidar data  $S_{k,\text{lidar}}$  by  $\sim 40 - 50\%$ , independently from the relative water depth (Figure 5b). This strong underestimation of the wave skewness is at least partly explained by the fact that wave crest elevations are consistently underestimated throughout the surf zone, even when most waves are broken (Figure 4b). Compared to  $S_{k,\text{hyd}}$ , the asymmetry  $A_{s,\text{hyd}}$  presents a slightly different behavior.  $A_{s,\text{hyd}}$  exhibits large relative differences compared to the free surface elevation asymmetry  $A_{k,\text{lidar}}$ , which decreases linearly with  $\mu$  (Figure 5c). The relative differences are approximately 45% for  $\mu > 0.26$  and decreases to approximately 25% in the inner surf zone, for  $\mu < 0.16$ . Overall, these large differences indicate that non-hydrostatic processes are important for the estimation of high-order surface elevation parameters. The large underestimation of the wave asymmetry in the inner surf zone is particularly surprising as one would expect the hydrostatic reconstruction to be more accurate in describing the sawtooth shape of long, broken waves, which are typical of inner surf zones. This point will be further analyzed in Section 5.

#### 4.2 Spectral shape and influence of a cutoff frequency on bulk parameters

To better understand the errors made in the shallowest parts of the surf zone, below we isolate a burst corresponding to waves propagating in the inner surf zone ( $\mu = 0.17$  and  $> 90\%$  of waves are broken, i.e.  $Q_b > 0.9$ ).

Figure 6 shows the energy density spectra  $S_\zeta$  computed for both  $\zeta_{\text{hyd}}$  and  $\zeta_{\text{lidar}}$  over this particular burst. Two energy peaks can be observed from these spectra. A

426 first peak at  $f = 0.02$  Hz corresponds to the infragravity motions dominating the inner  
 427 surf and swash zones during the experiments. The second peak, located at  $f = 0.1$  Hz,  
 428 corresponds to the peak frequency  $f_p$  of the incident short waves, which at this stage  
 429 of their propagation in the surf zone suffered much dissipation. Up to  $f \approx 0.3$  Hz,  
 430 both spectra exhibit similar shapes and levels of energy (Figure 6). However, large  
 431 differences on the spectra tails are observed for higher frequencies. The energy density  
 432 spectrum evaluated from  $\zeta_{\text{lidar}}$  displays a  $f^{-2}$  tail, characteristic of inner surf zone  
 433 waves (Kaihatu et al., 2007), while that evaluated from  $\zeta_{\text{hyd}}$  displays a  $f^{-7/2}$  tail,  
 434 which is, to the best of our knowledge, an undocumented behavior.

435 To analyze the effect of the differences in the tail shape and energy levels on  
 436 surface elevation bulk parameters, we investigate the effect of a potential cutoff fre-  
 437 quency  $f_c$  on the computation of these parameters. This was done by computing, for  
 438 varying  $f_c$ , the bulk parameters on the surface elevation signals that were low-pass  
 439 filtered at  $f_c$  with a Fourier-type filter. The results are shown in Figure 7. Up to  
 440  $f \sim 0.2$  Hz (twice the incident wave peak frequency), there are no differences between  
 441 the parameters computed from  $\zeta_{\text{hyd}}$  and  $\zeta_{\text{lidar}}$ . All parameters computed on  $\zeta_{\text{hyd}}$  reach  
 442 relatively stable values at  $f \sim 0.6$  Hz, with little variations when the cutoff is applied  
 443 at higher frequencies. This is explained by the much lower energy levels contained at  
 444 those frequencies in  $S_{\zeta, \text{hyd}}$  compared to  $S_{\zeta, \text{lidar}}$  (Figure 6). The divergence of the bulk  
 445 parameters computed from  $\zeta_{\text{hyd}}$  and  $\zeta_{\text{lidar}}$  with varying  $f_c$  emerge from the differences  
 446 in energy levels between 0.4 and 1 Hz, which is related to different surface elevation  
 447 spectral tails. The final relative errors for this burst are 8%, 52% and 26% for the sur-  
 448 face elevation variance (Figure 7a), skewness (Figure 7b) and asymmetry (Figure 7c)  
 449 respectively. Overall, these results suggest that, in the inner surf zone at least, non-  
 450 hydrostatic effects concentrate in the high frequency part of the elevation spectrum  
 451 ( $f > 2 - 3f_p$ ). These results also confirm the importance of incorporating spectral  
 452 information at high-frequencies in order to accurately describe second and third-order  
 453 surface elevation parameters, even in the inner surf zone. This is particularly true for  
 454 the wave skewness, which is very sensitive to the choice of  $f_c$ . For instance,  $f_c = 3f_p$   
 455 only leads to a value approximately half the real value.

## 456 5 Application of the reconstruction methods in the surf zone

457 The results from the previous section show that the spectral information at high  
 458 frequencies ( $f > 3f_p$ ) is needed in order to accurately estimate the surface eleva-  
 459 tion variance, skewness and asymmetry from sub-surface pressure measurements. In  
 460 this section, we apply the different reconstruction methods introduced earlier, and in  
 461 particular the non-linear weakly dispersive reconstruction method of Bonneton et al.  
 462 (2018), to the surf zone data collected at Saltburn.

463 For the present analysis, we isolate a burst corresponding to waves propagating  
 464 in the transitional region of the shoaling region and the outer surf zone, so that, with  
 465 the inner surf zone burst of Section 4, they represent the two extremes of the present  
 466 dataset. The outer surf zone burst is characterized by  $h_0 = 2.15$  m,  $\mu = 0.29$  and a  
 467 fraction of broken and breaking waves estimated at 9% ( $Q_b \sim 0.09$ ).

### 468 5.1 Spectral domain

469 Figures 8a and 8b show the energy density spectra  $S_\zeta$  of the different recon-  
 470 structed surface elevation signals for the outer and inner surf zone cases respectively.  
 471 In this Figure, we also show the equivalent transfer functions  $K_p$  for each of the recon-  
 472 struction (Figures 8c and 8d); these were computed as  $K_{p, \text{lin}} = S_{\zeta, \text{lin}}/S_{\zeta, \text{hyd}}$  and  
 473  $K_{p, \text{snl}} = S_{\zeta, \text{snl}}/S_{\zeta, \text{hyd}}$  for the linear and non-linear reconstruction respectively. These  
 474 equivalent transfer functions are compared against the ground truth ratio  $S_{\zeta, \text{lidar}}/S_{\zeta, \text{hyd}}$ ,

475 which effectively represents the transfer function required to pass from the hydrostatic  
476 reconstruction to the lidar data. In practice, this is the target transfer function.

477 Compared to the inner surf zone case, the energy density spectra from the outer  
478 surf zone burst displays quite different behaviours. In the outer surf zone, the energy  
479 peak corresponds to the incident short wave peak frequency  $f_p = 0.1$  Hz (Figure 8a).  
480  $S_{\zeta, \text{hyd}}$  is shown to underestimate the energy levels starting from the second harmonic  
481 only ( $f = 0.2$  Hz), while in the inner surf zone, the differences between  $S_{\zeta, \text{hyd}}$  and  
482  $S_{\zeta, \text{lidar}}$  remain small up to the fourth harmonic (Figure 8b). The latter point can also  
483 be observed in the good match between second and third-order parameters computed  
484 on the hydrostatic and lidar signals for  $f_c < 0.4$  Hz (Figure 7). In the spectrum tail,  
485 the difference between  $S_{\zeta, \text{hyd}}$  and  $S_{\zeta, \text{lidar}}$  is even larger for the outer surf zone case  
486 and reaches two orders of magnitude for  $f > 0.6$  Hz.

487 In Figures 8a and 8b, two signals reconstructed with the transfer function from  
488 linear theory (Eq. 3) are shown: a signal without cutoff frequency  $\zeta_{\text{lin}}$ , and  $\zeta_{\text{lin}, f_c}$ , a  
489 signal to which a cutoff  $f_{c, \text{lin}}$  was applied at frequencies where the transfer function  
490 starts to blow up. Without cutoff frequency,  $S_{\zeta, \text{lin}}$  deviates quite rapidly from  $S_{\zeta, \text{lidar}}$   
491 in both the outer (Figure 8a) and inner surf zone cases (Figure 8b). The levels of  
492 energy corrected with linear wave theory are almost one order of magnitude too high  
493 around  $f = 0.6$  Hz in the outer surf zone ( $K_{p, \text{lin}} \sim 100$ , Figure 8c), while this range  
494 of error is only reached at  $f = 1$  Hz in the inner surf zone (Figure 8d). As these  
495 frequencies are much lower than the frequency where noise in the measurements is  
496 dominant ( $f \sim 1.2$  Hz, see Appendix), we here provide more evidence that a cutoff  
497 frequency is needed with linear wave theory because of wave non-linearity and not  
498 only because of the presence of noise in the measurements. By analyzing the ratio  
499  $S_{\zeta, \text{lidar}}/S_{\zeta, \text{hyd}}$  in Figure 8c and 8d,  $K_{p, \text{lin}}$  can be considered inappropriate starting  
500 from  $f \sim 0.4$  Hz in the outer surf zone while this occurs around  $f \sim 0.5$  Hz in the inner  
501 surf zone. These frequencies were thus chosen as cutoff frequency  $f_{c, \text{lin}}$  to compute  
502  $\zeta_{\text{lin}, f_c}$ .

503 The use of a cutoff frequency in the linear reconstruction has slightly different  
504 consequences depending on the relative position in the surf zone. In the outer surf  
505 zone, the large differences in energy levels between  $S_{\zeta, \text{hyd}}$  and  $S_{\zeta, \text{lidar}}$  at frequencies  
506 between 0.2 and 0.4 Hz (Figure 8a) lead to considerable improvements of the estimates  
507 of wave parameters when using the linear reconstruction compared to the hydrostatic  
508 reconstruction (see Table 2). The error on the variance is reduced from 25.5% to 5.8%  
509 in the outer surf zone, compared to an improvement of only 6% in the inner surf zone  
510 (although, the error made with the hydrostatic reconstruction is already low, see Table  
511 3). As already seen in Figure 7, the need for a cutoff frequency limits the accuracy  
512 in the computation of third-order moments. Here, the relative errors on third-order  
513 moments for  $\zeta_{\text{lin}, f_c}$  remain above 30% in the outer surf zone and above 17% in the inner  
514 surf zone. In the inner surf zone, the difference in energy levels between  $S_{\zeta, \text{lidar}}$  and  
515  $S_{\zeta, \text{hyd}}$  are much smaller, which explains why the transfer function from linear wave  
516 theory only brings marginal improvement compared to the hydrostatic reconstruction  
517 due to the cutoff frequency (Table 3). This also explains why the hypothesis of a  
518 hydrostatic pressure field was sometimes made in the inner surf zone (Sénéchal et al.,  
519 2001).

520 For the two particular cases analyzed here, the non-linear weakly dispersive  
521 method of Bonneton et al. (2018) uses cutoff frequencies at least twice that used by the  
522 transfer function from linear wave theory. For the outer surf zone burst,  $f_{c, \text{snl}} = 0.9$  Hz  
523 (Figure 8a) while we use  $f_{c, \text{snl}} = 1.1$  Hz in the inner surf zone (Figure 8b). As ex-  
524 plained in the Appendix, imposing  $f_{c, \text{snl}} = 1.1$  Hz is close to be the upper limit for  
525 any burst from the present dataset, as noise in the pressure measurements becomes  
526 dominant at higher frequencies. The lower cutoff frequency used in the outer surf zone  
527 case is required due to important wave non-linearities. This is explained by the fact

528 that the non-linear method introduced by Bonneton et al. (2018) corrects the signal  
 529 reconstructed using linear wave theory (cf. Eq. 5 and 6), which is sensitive to the  
 530 choice of  $f_{c, \text{snl}}$ . This point is further discussed in the Appendix, especially from a  
 531 practical point of view. The fact that cutoff frequencies can be taken almost up to  
 532 where the noise in the measurements is strong allows the non-linear reconstruction  
 533 method to reach equivalent transfer function corrections of  $O(10^2)$  in the outer surf  
 534 zone (see around  $f = 1$  Hz in Figure 8c) and  $O(10)$  in the inner surf zone (for  $f > 1$  Hz,  
 535 see Figure 8d). For both cases, the correction coefficients match those corresponding  
 536 to the ratio  $S_{\zeta, \text{lidar}}/S_{\zeta, \text{hyd}}$ , meaning that the non-linear reconstruction correctly re-  
 537 produces the energy levels up to  $f = 1.2$  Hz (Figure 8). In the outer surf zone, the  
 538 corresponding relative error on the variance is close to 0%, while the error on the wave  
 539 skewness and asymmetry is as low as 5.7% and 14.9% respectively (Table 2). In the  
 540 inner surf zone (Figure 8b), the surface spectrum tail is well captured by the non-  
 541 linear reconstruction, and leads to similar performances for bulk parameters estimates  
 542 (relative errors  $< 6\%$  for all parameters, see Table 3). These can even be improved by  
 543 imposing a lower cutoff frequency (around 1 Hz), but the spectra tails do not match  
 544 anymore.

## 545 5.2 Temporal domain

546 Figure 9 shows the propagation of a wave group extracted from the outer surf  
 547 zone case. The capacity of the non-linear reconstruction to correctly represent the  
 548 energy density spectrum tail reflects from the good representation of the wave crest  
 549 elevations. This is not the case with the linear reconstruction, which consistently  
 550 underestimates the maximum elevations, especially for the steepest waves. This is  
 551 well illustrated with the fifth wave of the group, which is just about to break and can  
 552 be considered as an extreme wave since  $\zeta_c/H_s = 1.85$ , where  $\zeta_c$  is the crest elevation  
 553 (e.g., see Dysthe et al., 2008). For this particular wave, the error on the crest elevation  
 554 is approximately 35% with the linear reconstruction (Figure 9), a number which is  
 555 consistent with Martins et al. (2017a) and Mouragues et al. (2019). As mentioned in  
 556 the previous section, the cutoff frequencies for this example are  $f_{c, \text{lin}} = 0.4$  Hz and  
 557  $f_{c, \text{snl}} = 0.9$  Hz.

558 A closer look at the extreme wave in the group is given in Figure 10. As observed  
 559 in Figures 9 and 10b, the pressure field is mostly hydrostatic at the trough level;  
 560 this is in agreement with the observations from Section 4. The neglect (hydrostatic  
 561 reconstruction) or underestimation (linear reconstruction) of the fluid acceleration  
 562 leads to an overestimation of the surface elevation  $\zeta_{\text{hyd}}$  and  $\zeta_{\text{lin}, f_c}$  as the wave face  
 563 approaches (Figure 10c). Under the crest, only the non-linear reconstruction can  
 564 well approximate the sharp crested shape of the wave, while the linear reconstruction  
 565 brings only little improvement compared to the hydrostatic reconstruction for such an  
 566 extreme wave (Figures 10d and 10e). At the back of the wave,  $\zeta_{\text{hyd}}$  and  $\zeta_{\text{lin}, f_c}$  tend to  
 567 be overestimated, before matching well again the direct measurements at the following  
 568 trough. In agreement with recent studies (e.g., see Bonneton et al., 2018), we find  
 569 relative errors of 26.7% and 28.7% for the variance and skewness respectively, when  
 570 computed on the surface elevation reconstructed with linear wave theory  $\zeta_{\text{lin}, f_c}$ . These  
 571 errors decrease to 7.6% and 6.0% respectively with the non-linear weakly dispersive  
 572 method. Overall, these errors are well illustrated with the spatial transformation of the  
 573 breaking wave shown by the lidar data, which highlights the volume of water missed  
 574 near the crest with the hydrostatic and linear reconstructions (Figures 10b-g).

575 Comparisons of reconstructed surface elevation time series are also performed for  
 576 the inner surf zone burst and are shown in Figure 11. In this region of the surf zone, the  
 577 hydrodynamics is dominated by long, sawtooth-shaped, broken waves. Although most  
 578 waves display an overall sawtooth shape, they also exhibit a sharp, small crest at the  
 579 wave front (see for instance Figure 11b). These sharp crests are systematically missed

580 by the linear and hydrostatic reconstructions (Figure 11a). Furthermore, the zoom in  
 581 Figure 11b demonstrates the very little differences between the two reconstructions,  
 582 which is consistent with earlier observations and Table 3. Not only the crests are  
 583 missed, but the front wave slope is smoothed, and explains why third-order moments  
 584 are strongly underestimated with the hydrostatic and linear reconstruction methods,  
 585 even in the inner surf zone. In contrast, the non-linear weakly dispersive reconstruction  
 586 method shows great skill in describing the shapes of individual inner surf zone  
 587 waves. Wave crests elevations are much better described compared to  $\zeta_{\text{hyd}}$  and  $\zeta_{\text{lin}, f_c}$ ,  
 588 and only the largest wave shows some underestimation of the real elevation (Figure  
 589 11b). Typical errors on individual wave heights over this burst decrease from approx-  
 590 imately 20% with linear wave theory to around 10% for the largest waves. Further,  
 591 the wave face slope is also much better described by the non-linear reconstruction,  
 592 which is consistent with the match between  $S_{\zeta, \text{snl}}$  and  $S_{\zeta, \text{lidar}}$  at high frequencies.  
 593 More importantly, this suggests that the hypothesis upon which the non-linear weakly  
 594 dispersive formula is built, i.e. that the flow is irrotational, is applicable under broken  
 595 waves.

### 596 5.3 Performances of the reconstruction methods

597 Figure 12 summarizes, for the present dataset, the performances of the different  
 598 reconstruction methods to describe second (variance) and third-order ( $S_k$  and  $A_s$ )  
 599 surface elevation bulk parameters. It is worth noting that in this Section, the cutoff  
 600 frequencies  $f_{c, \text{lin}}$  and  $f_{c, \text{snl}}$  vary for each burst and were optimized by visually checking  
 601  $S_{\zeta}$ .

602 Following the observations from Section 4, the relative difference on the surface  
 603 elevation variance made with the hydrostatic reconstruction remains relatively con-  
 604 stant (between 25 and 30%) for  $\mu > 0.20$  (Figure 12a). It is only for  $\mu < 0.20$ , which  
 605 corresponds to  $Q_b > 0.7 - 0.8$ , that the relative differences decrease. This suggests that  
 606 non-hydrostatic effects are strong everywhere in the surf zone and weaken only when  
 607 most waves are broken. Inappropriate definitions of the inner surf zone in regards to  
 608 breaker indexes (e.g. when the occurrence of wave breaking is still important) or other  
 609 wave parameters might hence lead to large errors on wave parameters estimates if the  
 610 hydrostatic reconstruction is preferred over those regions (e.g., Sénéchal et al., 2001).  
 611 Although it suffers from the need of a cutoff frequency, the transfer function based  
 612 on linear wave theory systematically improves the estimates of the surface elevation  
 613 variance to within 10% on average. It is worth noting that the wave energy in the inner  
 614 surf zone is hence better described with linear wave theory than with the hydrostatic  
 615 reconstruction, as long as the cutoff frequency is correctly chosen. Ultimately, using  
 616 the non-linear weakly dispersive reconstruction method of Bonneton et al. (2018) leads  
 617 to errors on the variance inferior to 5% on average, independently from the local water  
 618 depth.

619 As opposed to the surface variance, third-order parameters (Figures 12b and 12c)  
 620 are not much better predicted with linear wave theory. Compared to the hydrostatic  
 621 reconstruction, the relative error on  $A_s$  is roughly halved (Figure 12c), while that on  
 622  $S_k$  is reduced by approximately 10% on average but remains high ( $> 30\%$  on average)  
 623 anywhere in the surf zone (Figure 12b). Except for  $\mu \sim 0.24$ , where the average error  
 624 on  $A_s$  is approximately 15%, the non-linear weakly dispersive reconstruction leads to  
 625 errors inferior to 5% on average for both parameters.

## 626 6 Conclusions

627 We use sub-surface pressure and surface elevation lidar data collected at the  
 628 macrotidal, dissipative site of Saltburn-by-the-Sea, UK, to study the non-hydrostatic  
 629 and non-linear character of surf zone waves. The results presented in Section 4 inform

630 us that non-hydrostatic effects remain important in the entire surf zone. In the inner  
 631 surf zone, where the pressure field is generally assumed hydrostatic, the variance of  
 632 the surface elevation computed on the hydrostatic reconstruction is underestimated  
 633 by 10% on average (Figure 12a). Consistent with earlier observations, non-hydrostatic  
 634 effects concentrate in a relatively small region around the wave face (see illustration  
 635 in Figure 1) and have two consequences on the reconstructed wave profile: wave crests  
 636 elevation are underestimated and the elevation profile near the broken wave front is  
 637 smoothed. As a consequence, surface elevation skewness and asymmetry estimate on  
 638  $\zeta_{\text{hyd}}$  show underestimations larger than 40% and 20% respectively in this region of the  
 639 surf zone (Figures 12b and 12c), despite the fact that broken waves exhibit an overall  
 640 sawtooth shape (e.g., see Figure 11).

641 As long as the cutoff frequency  $f_{c, \text{lin}}$  is carefully chosen, the transfer function  
 642 based on linear wave theory improves the estimation of surface elevation bulk param-  
 643 eters over the entire surf zone (Figure 12). For instance, the variance of the surface  
 644 elevation (and hence the energy) is correct within 10% on average, for optimised  $f_{c, \text{lin}}$ .  
 645 However, the cutoff frequency, needed to prevent the overestimation of the transfer  
 646 function, is a severe constraint in the accurate representation of energy levels at  
 647 frequencies higher than  $f = 3 - 6f_p$  (Figures 7a and 7b). This results in a large  
 648 underestimation of the wave crest elevation and third-order parameters, even in the  
 649 inner surf zone, where we show that  $\zeta_{\text{lin}, f_c}$  also smooths the steep broken wave face  
 650 profile (Figures 10a and 10b).

651 For optimised cutoff frequencies, the non-linear weakly dispersive formula from  
 652 Bonneton et al. (2018) leads to relative errors of 5% on average for all parameters ana-  
 653 lyzed here (Figure 12), except for large  $\mu$  where larger errors are obtained for the wave  
 654 asymmetry. Note that in this region of the surf zone, the wave asymmetry is relatively  
 655 small. The performances of this formula in the inner surf zone (Figure 11) demonstrate  
 656 that the hypothesis of the flow being irrotational under broken waves is appropriate,  
 657 which was not expected. These results also indirectly support the approach made by  
 658 Lucarelli et al. (2018) that the bottom layer under spilling breakers is characterized by  
 659 an irrotational flow. None of the reconstruction methods presented here account for  
 660 the rotational and turbulent part of the flow, which concentrates around the active part  
 661 of the breaker (surface roller, Figure 1). However, the performances of the non-linear  
 662 formula demonstrate that these effects should have little impact on the dominant flow  
 663 associated with the wave propagation. Similarly, the presence of large fractions of air  
 664 near the broken wave face might only be perceived by the lidar, which could explain  
 665 the slight underestimation of crest elevations in the reconstructed signals. Elsewhere  
 666 in the surf zone, splashes generated by breaking were not found to have any effect  
 667 on quantities derived from the lidar dataset, which is explained by the large variabil-  
 668 ity in the breaking point location. Along with the use of the cutoff frequency  $f_{c, \text{snl}}$ ,  
 669 non-hydrostatic effects from the roller and fundamental differences in the measuring  
 670 techniques (around breaking and due to entrained air) might explain the differences  
 671 obtained with the non-linear reconstruction method.

672 These findings open up several research perspectives for surf zone hydrodynamics,  
 673 some of which are discussed here. The first point regards surf zone wave statistics  
 674 obtained in the field with pressure sensors and linear wave theory, and possibly in some  
 675 laboratory studies that employed resistive type of wave gauges (Section 2.1). Unlike  
 676 the classic transfer function, the non-linear weakly dispersive formula is clearly adapted  
 677 to wave-by-wave analyses and will allow the derivation of more accurate wave statistics  
 678 in the field (e.g. wave height distribution and extrema). In particular, wave height  
 679 distributions are used in most nearshore circulation models and are thus of paramount  
 680 importance. The second point developed here regards the approach used to deal with  
 681 wave breaking processes in fully non-linear, non-hydrostatic models. We have shown  
 682 that intense non-hydrostatic wave effects are localized very close to the turbulent wave



683 front (see Figure 1). This leads to great difficulties in modelling the localized energy  
 684 dissipation without affecting the non-hydrostatic quasi-potential wave field. Hence,  
 685 classical breaking parametrizations in fully non-linear non-hydrostatic models, either  
 686 based turbulent viscosity or shock-wave approaches, tend to round-off the highest  
 687 wave crests. For these reasons, it is crucial to improve breaking parametrizations in  
 688 phase-resolving models.

## 689 Appendix A On the choice of the cutoff frequency $f_c$

690 To reconstruct the free surface elevation, both the classic transfer function method  
 691 (Eq. 2) and the non-linear weakly dispersive reconstruction method (Eq. 6) need cut-  
 692 off frequencies. In Section 5, the performances of these two reconstruction methods  
 693 were assessed with optimized cutoff frequencies, meaning that the relative errors pro-  
 694 vided in this study are very close to the minimum errors that can be reached with  
 695 the present dataset. In practice, the energy density of the free surface elevation is not  
 696 known, and robust criterion are desirable for the pressure correction.

697 As described earlier in the manuscript,  $f_{c, \text{snl}}$  varied considerably in the surf zone,  
 698 as a function of wave non-linearities. This is explained by the fact that the non-linear  
 699 formula uses and corrects a linear, shallow water reconstruction that is still sensitive to  
 700 wave non-linearities. For large  $\mu$  in the present dataset, values down to 0.6-0.65 Hz were  
 701 taken for  $f_{c, \text{snl}}$ . These values correspond to bursts for which  $f_{c, \text{lin}}$  were the smallest  
 702 (i.e. 0.35-0.40 Hz). It is worth noting that  $f_{c, \text{snl}}$  is systematically greater than  $f_{c, \text{lin}}$  by  
 703 a factor between 1.5 and 2 in the present dataset. In other cases, noise in the pressure  
 704 measurements is the most limiting factor. This noise, which can be identified where  
 705 the elevation spectrum tail flattens (e.g., Smith, 2002), can have several origins: the  
 706 power system, the pressure transducer or the flow disturbance (Cavaleri, 1980; Bishop  
 707 and Donelan, 1987; Smith, 2002). Here, the noise level is easily identified in  $S_{\zeta, \text{hyd}}$   
 708 over the entire surf zone (see Figure A1, for the outer and inner surf zone bursts):  
 709 the noise dominates at frequencies higher than approximately 1.2 Hz, which will be  
 710 referred to as  $f_{c, \text{noise}}$  in the following. Similar to the data collected in the shoaling  
 711 region by Bonneton et al. (2018) and Mouragues et al. (2019), noise in the pressure  
 712 data is thus the limiting factor for some of the bursts, which are characterized by  
 713 relatively low  $\mu$  values, and for which  $f_{c, \text{snl}}$  was taken up to 1.2 Hz.  $f_{c, \text{noise}}$  defines  
 714 the upper bound for  $f_{c, \text{snl}}$ , however, it will differ with the type of pressure sensor  
 715 used and will vary with the deployment procedures, the hydrodynamic conditions etc.  
 716 Displaying surface elevation spectra as in Figure A1 can help defining an upper bound  
 717 for the cutoff frequency.

718 For the linear transfer function (Eq. 3), Smith (2002) suggest that  $f_{c, \text{lin}}$  should  
 719 be chosen so that  $|K_{p, \text{lin}}|^2 < 100 - 1000$ . In Section 5, we show that  $|K_{p, \text{lin}}|^2 <$   
 720  $25 - 100$  and  $|K_{p, \text{lin}}|^2 < 4 - 10$  are the maximum range before the transfer function  
 721 is overestimated for the outer and surf zone cases respectively (Figures 8c and 8d).  
 722 This suggests that the validity range for  $K_{p, \text{lin}}$  varies with the relative water depth.  
 723 Figure A2 shows the ratio  $K_{p, \text{lidar}} = S_{\zeta, \text{lidar}}/S_{\zeta, \text{hyd}}$  for every burst, which effectively  
 724 represents the observed transfer function. The abrupt change of slope around  $f =$   
 725  $1.2$  Hz confirms that above this frequency, the noise dominates the spectrum, since the  
 726 correction should increase with  $f$ . Below this pivot frequency,  $K_{p, \text{lidar}}$  increases with  
 727  $\mu$ , confirming the point made above. This also highlights the difficulty to define both  
 728  $f_{c, \text{lin}}$  and  $f_{c, \text{snl}}$  based on a threshold value in the corresponding transfer function.

729 For now, both  $f_{c, \text{lin}}$  and  $f_{c, \text{snl}}$  are best chosen by carefully looking at elevation  
 730 spectral tails: when the chosen value is too high, slope changes in  $S_{\zeta, \text{lin}}$  and  $S_{\zeta, \text{snl}}$   
 731 tails can be witnessed. As seen in Figure 8,  $f_{c, \text{lin}}$  is easily chosen, since the change  
 732 in the spectrum tail is very abrupt. The situation with the non-linear weakly dis-  
 733 persive reconstruction method is somewhat different, as quadratic interactions among

734 the fundamental modes fill the elevation spectrum beyond the cutoff frequency (Bon-  
 735 neton and Lannes, 2017). Hence, the slope change is much milder in the non-linear  
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**Tables**

**Table 1.** List of symbols. For the variables associated with the different reconstruction methods ( $\zeta$ ,  $K_p$  and  $f_c$ ), we use the subscript 'hyd', 'lin' and 'snl' to refer to the hydrostatic (Eq. 1), linear (Eq. 2) and non-linear (Eq. 6) reconstruction methods respectively. The subscript 'lidar' refers to the direct lidar measurements.

Symbol	Description	Unit
$\tan \beta$	beach slope	-
$\delta_m$	height of the pressure sensor above the bed	m
$\zeta$	free surface elevation	m
$\zeta_c$	wave crest elevation	m
$\mu$	dispersion (shallowness) parameter ( $\mu = kh_0$ )	-
$\omega$	radial frequency	rad.s <sup>-1</sup>
$f$	frequency	s <sup>-1</sup>
$f_c$	cutoff frequency	s <sup>-1</sup>
$f_p$	peak wave frequency	s <sup>-1</sup>
$g$	acceleration of gravity	m.s <sup>-2</sup>
$h_0$	mean water depth	m
$H$	wave height	m
$H_s$	significant wave height	m
$k$	wave number	rad.m <sup>-1</sup>
$K_p$	Transfer function	-
$t$	time	s
$T$	wave period	s
$T_p$	peak wave period	s
$x$	horizontal coordinate	m
$z$	vertical coordinate	m

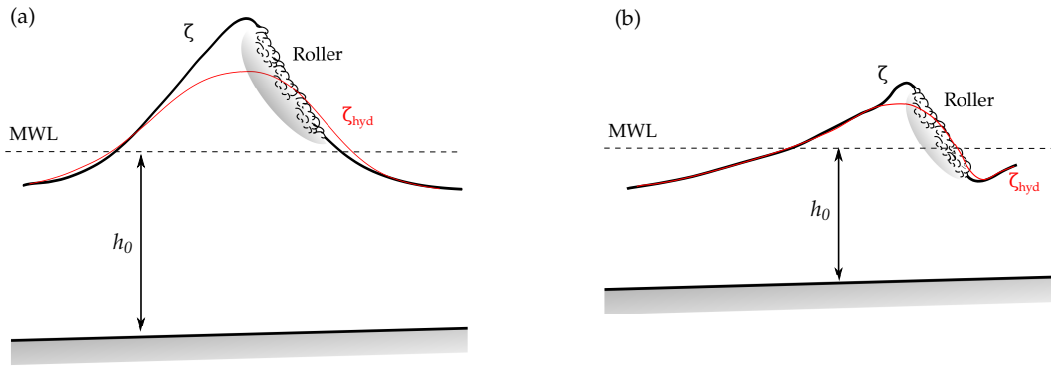


**Table 2.** Relative errors made by the different reconstruction methods for the outer surf zone burst (Figure 8a,  $h_0 = 2.15$  m,  $\mu = 0.29$  and  $H_s = 1.10$  m). For this burst, the cutoff frequencies used are  $f_{c, \text{lin}} = 0.4$  Hz for the linear reconstruction and  $f_{c, \text{snl}} = 0.9$  Hz for the non-linear weakly dispersive reconstruction.

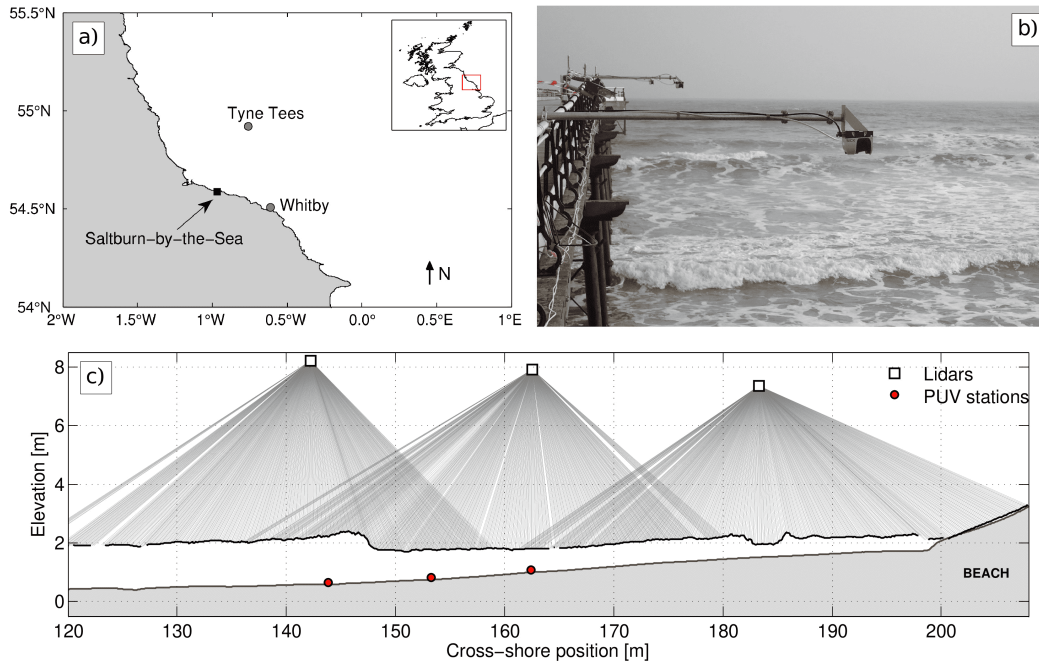
Quantity	$\zeta_{\text{lidar}}$	$\zeta_{\text{hyd}}$	$\zeta_{\text{lin}, f_c}$	$\zeta_{\text{snl}}$
Variance [m <sup>2</sup> ]	0.073	0.054	0.069	0.073
Variance error	-	25.5%	5.8%	0%
$S_k$ [-]	1.81	1.00	1.21	1.70
$S_k$ error	-	44.3%	33.1%	5.9%
$A_s$ [-]	-0.52	-0.29	-0.36	-0.43
$A_s$ error	-	43.9%	30.5%	16.2%

**Table 3.** Relative errors made by the different reconstruction methods for the inner surf zone burst (Figure 8b,  $h_0 = 0.76$  m,  $\mu = 0.17$  and  $H_s = 0.44$  m). For this burst, the cutoff frequencies used are  $f_{c, \text{lin}} = 0.5$  Hz for the linear reconstruction and  $f_{c, \text{snl}} = 1.1$  Hz for the non-linear weakly dispersive reconstruction.

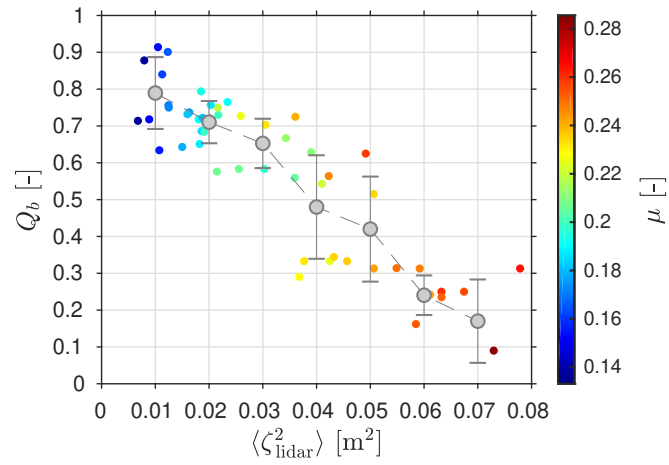
Quantity	$\zeta_{\text{lidar}}$	$\zeta_{\text{hyd}}$	$\zeta_{\text{lin}, f_c}$	$\zeta_{\text{snl}}$
Variance [m <sup>2</sup> ]	0.012	0.011	0.012	0.013
Variance error	-	8.1%	1.7%	4.3%
$S_k$ [-]	0.75	0.52	0.56	0.80
$S_k$ error	-	31.1%	25.4%	6.9%
$A_s$ [-]	-1.07	-0.79	-0.88	-1.05
$A_s$ error	-	25.8%	17.6%	1.6%

**Figures**

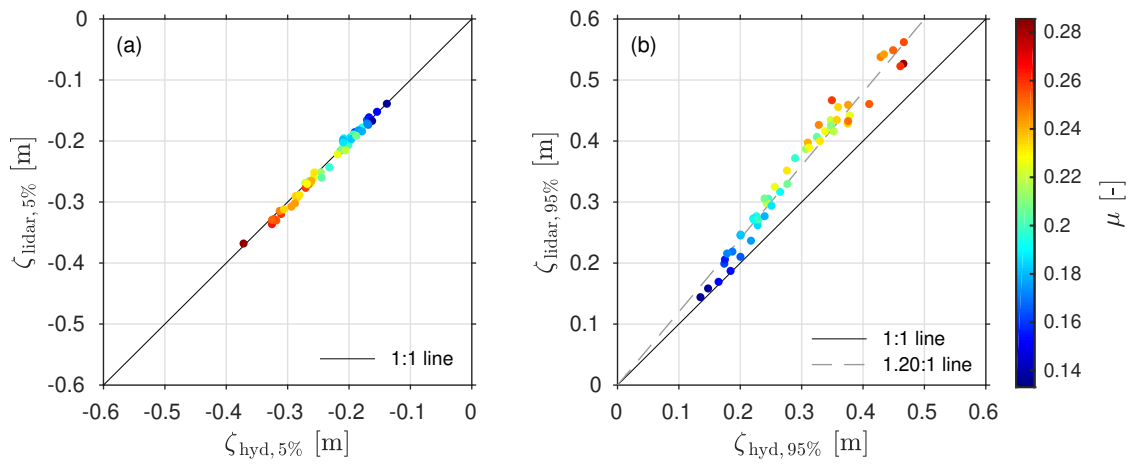
**Figure 1.** Illustrative sketch of the free surface elevation for surf zone waves propagating in the outer (a) and inner (b) surf zones.  $\zeta$  represents the free surface elevation while  $\zeta_{\text{hyd}}$  corresponds to the surface elevation reconstructed with the hypothesis that the pressure field is hydrostatic. *MWL* refers to the Mean Water Level while  $h_0$  is the mean water depth. Note that for plunging cases, the situation is more complex than depicted in panel (a), but effectively, the breaking wave can exhibit such shape after the splash-up phase. Near the breaking point, the overestimation of the free surface elevation by  $\zeta_{\text{hyd}}$  in front of the wave face is even more pronounced (see for instance Figure 2 in Martins et al., 2017a).



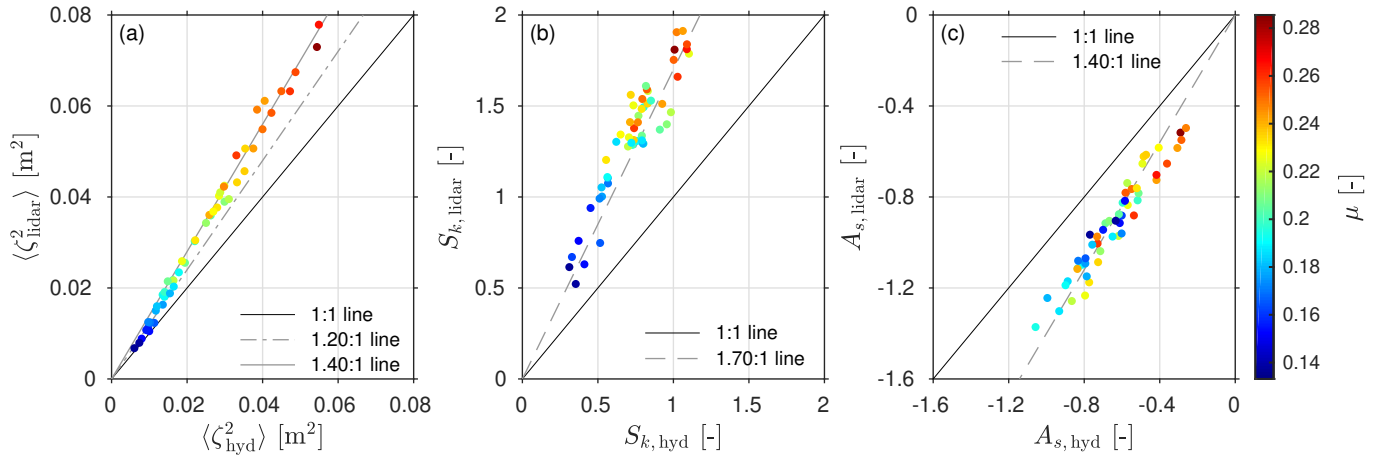
**Figure 2.** Field site and lidar scanner deployment during the April 2016 experiments at Saltburn-by-the-Sea, UK (modified from Martins et al., 2018). Panel (a) shows the regional map around Saltburn and the location of nearshore (Whitby) and offshore (Tyne Tees) wave buoys (grey dots). The lidar scanner deployment on the nearshore pier is depicted in panel (b): the scanners were deployed 2.5 m away from the pier, using a 'T'-shaped scaffolding system directly fixed to the pier railing. Panel (c) presents a schematic of the experimental setup with an example of post-processed free surface elevation (black thick line while individual measurements are shown as light grey lines). The beach profile (thick grey line) corresponds to the surveyed profile during the previous low tide (10 April 2016).



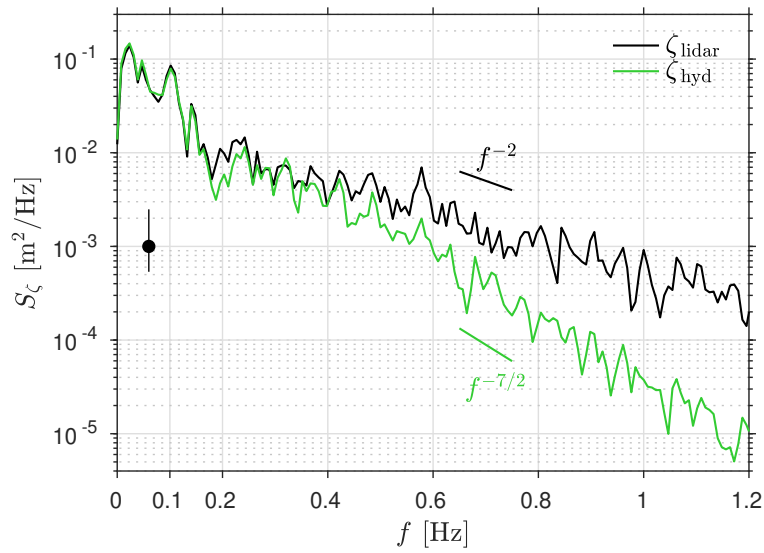
**Figure 3.** Fraction of breaking and broken waves  $Q_b$  at the most offshore ADV location as a function of the surface elevation variance  $\langle \zeta_{\text{lidar}}^2 \rangle$  computed on the lidar data. Individual burst data point are coloured by the value of the relative water depth  $\mu$  over that particular burst. Binned data (mean and standard deviation shown every 0.01 m<sup>2</sup>) are shown as grey dots and associated vertical bars.



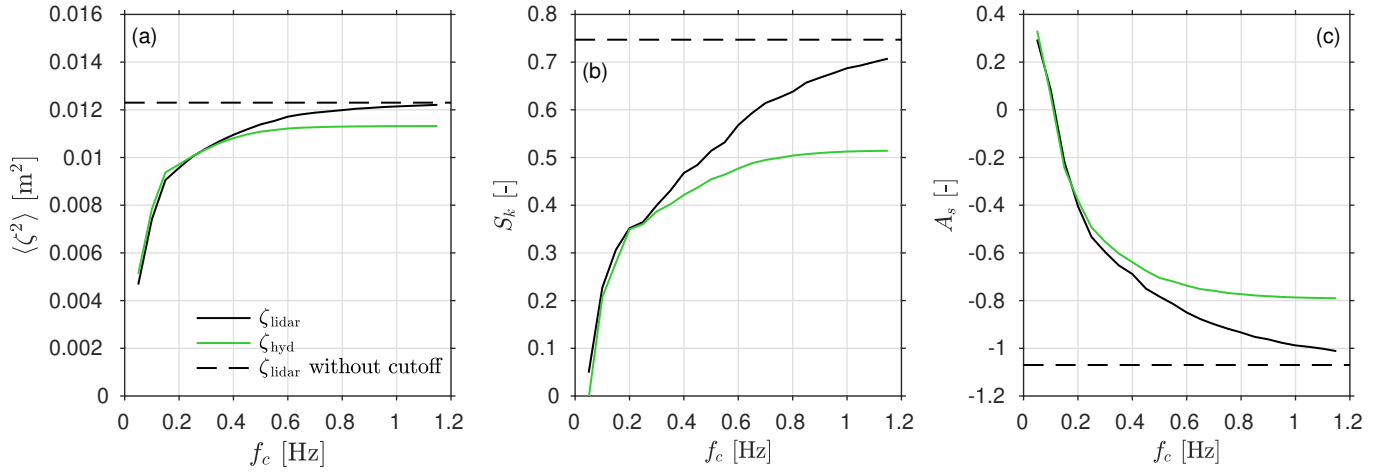
**Figure 4.** Comparison of the 5% (panel a) and 95% (panel b) surface elevation percentiles computed on the reconstructed signal  $\zeta_{\text{hyd}}$  with the direct lidar measurements  $\zeta_{\text{lidar}}$ . Individual burst data point are coloured by the value of the relative water depth  $\mu$  over that particular burst.



**Figure 5.** Comparison of second and third-order bulk parameters computed on the reconstructed surface elevation  $\zeta_{\text{hyd}}$  with the direct lidar measurements  $\zeta_{\text{lidar}}$ . Panel (a) shows the variance of the surface elevation (wave energy) while panel (b) and (c) show the comparisons between the surface elevation skewness and asymmetry respectively. Individual burst data point are coloured by the value of the relative water depth  $\mu$  over that particular burst.

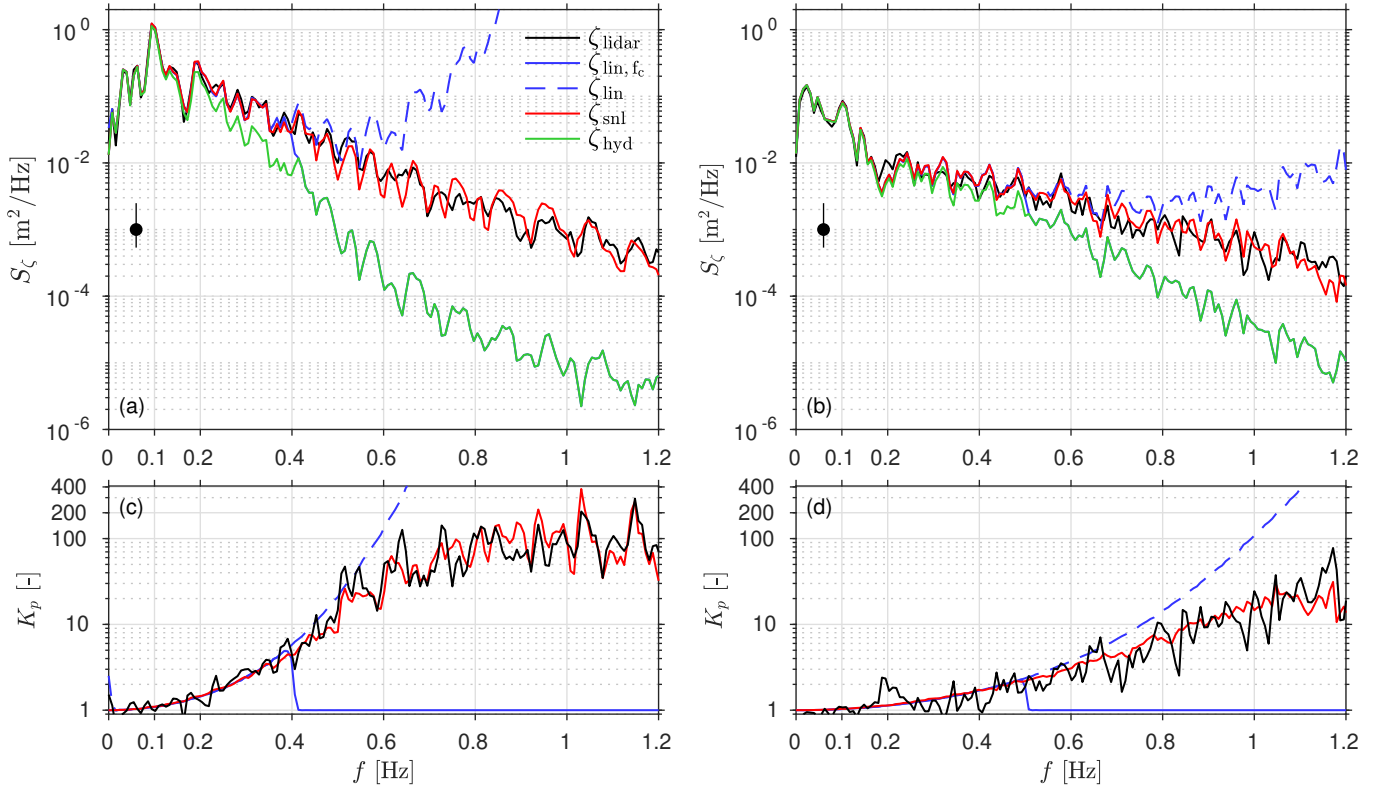


**Figure 6.** Energy density spectra  $S_\zeta$  of the reconstructed  $\zeta_{\text{hyd}}$  and directly measured  $\zeta_{\text{lidar}}$  surface elevation signals for the inner surf zone burst. Spectra were computed using Welch’s method with 7 Hann-windowed, 128 second segments overlapping by 50%, which results in energy density spectral estimates having approximately 13 degrees of freedom and a spectral resolution of 0.0078 Hz. The 90% confidence interval is shown as the black dot with the vertical bars

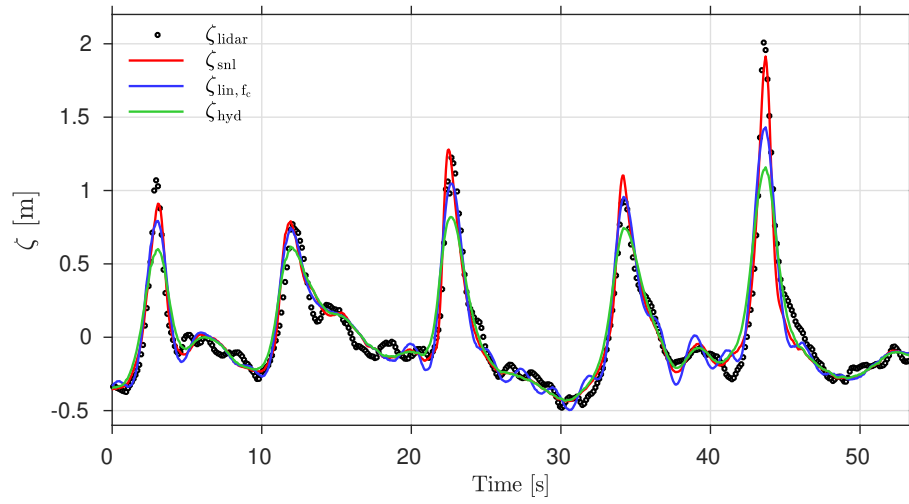


**Figure 7.** Second and third-order surface elevation parameters for the inner surf zone burst, computed with different cutoff frequency  $f_c$  and the original lidar signal. Panel (a) shows the variance while the skewness and asymmetry are shown in panels (b) and (c) respectively.

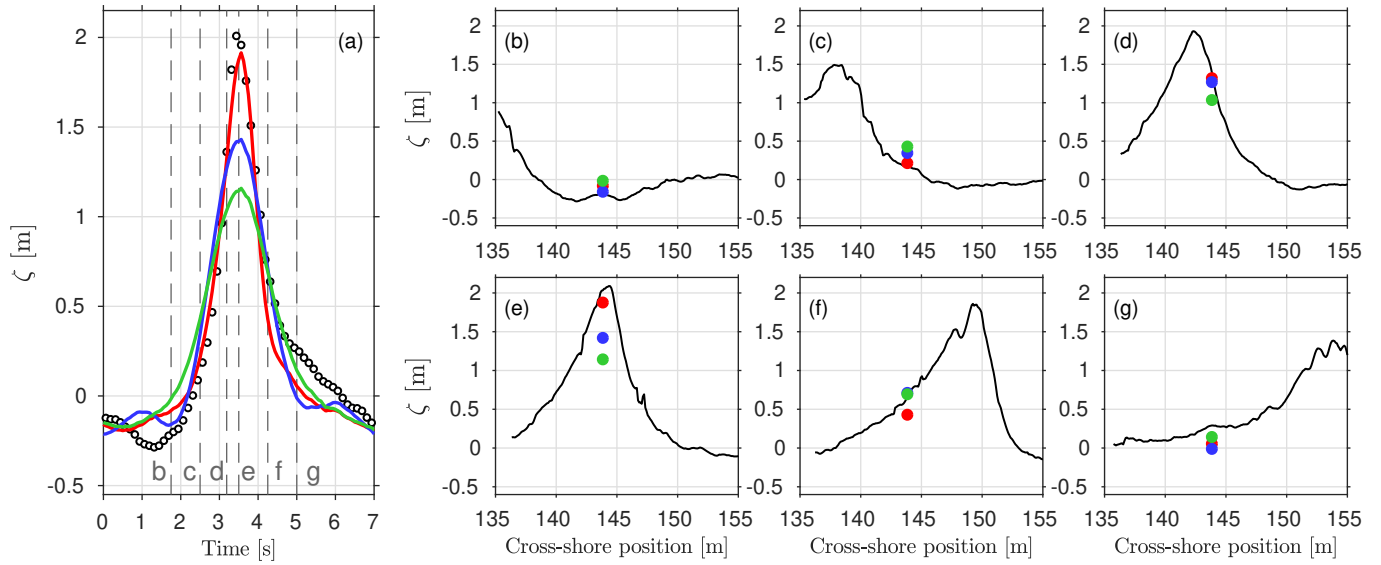




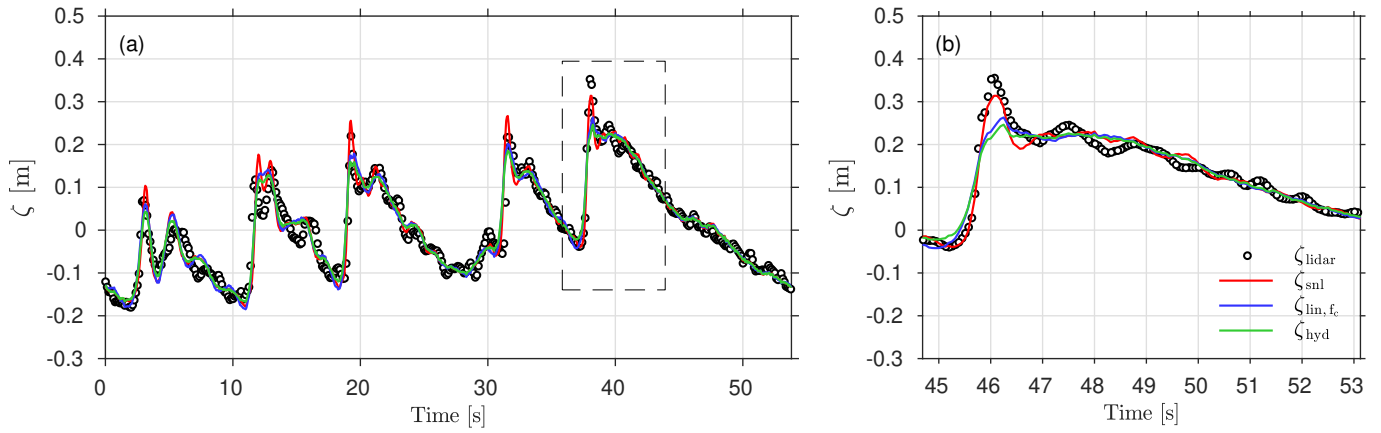
**Figure 8.** Energy density spectra  $S_\zeta$  of the reconstructed  $\zeta_{\text{hyd}}$ ,  $\zeta_{\text{lin}, f_c}$ ,  $\zeta_{\text{lin}}$ ,  $\zeta_{\text{snl}}$  and directly measured  $\zeta_{\text{lidar}}$  surface elevation signals for two contrasting cases: (a) outer surf zone, and (b) inner surf zone. For both cases, the equivalent transfer function  $K_p$  for each reconstruction methods is shown below the corresponding panel (c: outer surf zone, and d: inner surf zone).  $\zeta_{\text{lin}, f_c}$  corresponds to the linear reconstruction with a cutoff frequency of  $f_{c, \text{lin}} = 0.4$  Hz in the outer surf zone and  $f_{c, \text{lin}} = 0.5$  Hz in the inner surf zone. The cutoff frequencies for the non-linear weakly dispersive reconstruction are  $f_{c, \text{snl}} = 0.9$  Hz in the outer surf zone and  $f_{c, \text{lin}} = 1.1$  Hz in the inner surf zone. Note that in panels (c) and (d), the black line corresponds to the observed transfer function  $S_{\zeta, \text{lidar}}/S_{\zeta, \text{hyd}}$ . Spectra were computed using Welch's method with 7 Hann-windowed, 128 second segments overlapping by 50%, which results in energy density spectral estimates having approximately 13 degrees of freedom and a spectral resolution of 0.0078 Hz. The 90% confidence interval is shown as the black dot with the vertical bars.



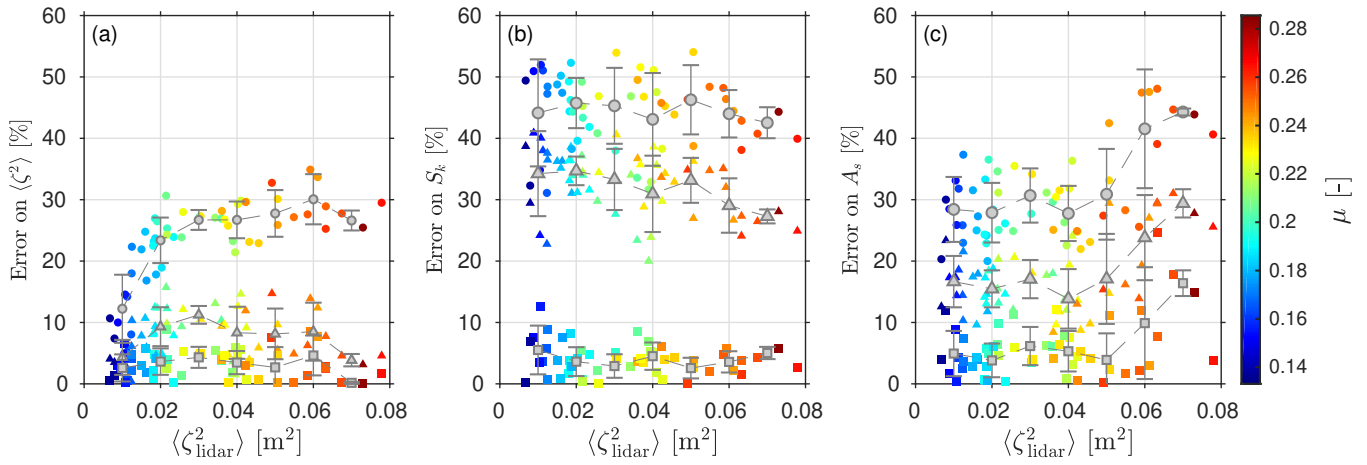
**Figure 9.** Surface elevation reconstructions and direct lidar measurements for a wave group extracted from the outer surf zone burst. The cutoff frequencies for this example are  $f_{c, \text{lin}} = 0.4 \text{ Hz}$  and  $f_{c, \text{snl}} = 0.9 \text{ Hz}$ . For readability, lidar data is shown every two points.



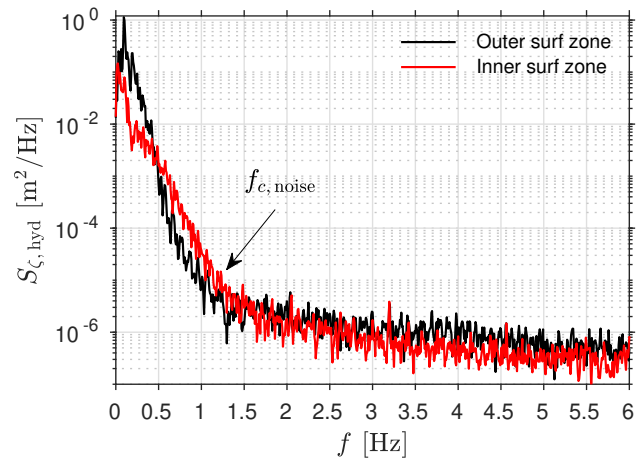
**Figure 10.** Surface elevation reconstructions and lidar measurements for the extreme wave extracted from the group presented in Figure 9. Panel (a) shows the free surface elevation time series (same color code as Figure 9: circles are for lidar data while red, blue and green lines are for  $\zeta_{\text{snl}}$ ,  $\zeta_{\text{lin}, f_c}$  and  $\zeta_{\text{hyd}}$  respectively). Panels (b) to (g) display the spatial information from the lidar data (black line) along with the corresponding pressure-derived data points (same color code as panel a) at 6 specific moments, indicated in panel (a) as gray dashed vertical lines. The cutoff frequencies for this example are  $f_{c, \text{lin}} = 0.4$  Hz and  $f_{c, \text{snl}} = 0.9$  Hz.



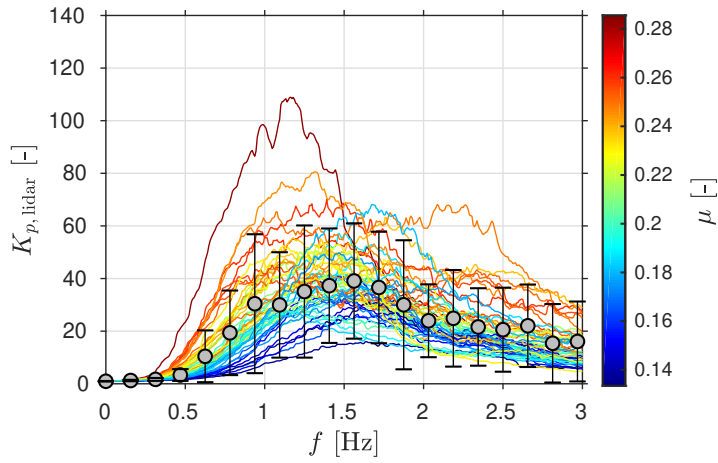
**Figure 11.** Surface elevation reconstructions and direct lidar measurements for a group of broken waves propagating in the inner surf zone. Panel (a) shows the free surface elevation time series over the group while panel (b) shows a zoom around the largest wave of the group (the corresponding wave is highlighted with the dashed rectangle in panel a). The cutoff frequencies for this example are  $f_{c, \text{lin}} = 0.5 \text{ Hz}$  and  $f_{c, \text{snl}} = 1.1 \text{ Hz}$ . For readability, lidar data is shown every two points in panel a.



**Figure 12.** Error made on the surface elevation variance (Panel a), skewness (Panel b) and asymmetry (Panel c) by the different reconstruction methods for every burst of the present dataset. Squares correspond to  $\zeta_{\text{snl}}$  data points while triangles and dots are for  $\zeta_{\text{lin,fc}}$  and  $\zeta_{\text{hyd}}$  respectively. Individual burst data point are coloured by the value of the relative water depth  $\mu$  over that particular burst. Binned data (mean and standard deviation shown every  $0.01 \text{ m}^2$ ) are shown as grey dots and associated vertical bars.



**Figure A1.** Energy density spectra for the outer and inner surf cases, shown up to 6 Hz. The noise starts to dominate at frequencies higher than approximately 1.2 Hz.



**Figure A2.** Ratio  $K_{p, \text{lidar}} = S_{\zeta, \text{lidar}}/S_{\zeta, \text{hyd}}$  for every burst. As the energy density spectra are quite peaky, the ratio were window-averaged using a window 0.5 Hz-wide. Each line corresponds to a burst and was coloured by the value of the relative depth  $\mu$  during this burst. Binned data (mean and standard deviation shown every 0.15 Hz) are shown as grey dots and associated vertical bars.