

**Wave Transformation Across a Macrotidal Shore Platform  
Under Low to Moderate Energy Conditions**

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## Wave Transformation Across a Macrotidal Shore Platform Under Low to Moderate Energy Conditions

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67 **Abstract**

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9 23 We investigate how waves are transformed across a shore platform as this is a  
10  
11 24 central question in rock coast geomorphology. We present results from deployment  
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13 25 of three pressure transducers over four days, across a sloping, wide (~200 m) cliff-  
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15 26 backed shore platform in a macrotidal setting, in South Wales, United Kingdom.  
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17 27 Cross shore variations in wave heights were evident under the predominantly low to  
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19 28 moderate (significant wave height < 1.4 m) energy conditions measured. At the  
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21 29 outer transducer 50 m from the seaward edge of the platform (163 m from the cliff)  
22  
23 30 high tide water depths were 8+ m meaning that waves crossed the shore platform  
24  
25 31 without breaking. At the mid platform position water depth was 5 m. Water depth at  
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27 32 the inner transducer (6 m from the cliff platform junction) at high tide was 1.4 m. This  
28  
29 33 shallow water depth forced wave breaking, thereby limiting wave heights on the inner  
30  
31 34 platform. Maximum wave height at the middle and inner transducers were 2.41 and  
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33 35 2.39 m respectively and significant wave height 1.35 m and 1.34 m respectively.  
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35 36 Inner platform high tide wave heights were generally larger where energy was up to  
36  
37 37 335% greater than near the seaward edge where waves were smaller. Infragravity  
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39 38 energy was less than 13% of the total energy spectra with energy in the swell, wind  
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41 39 and capillary frequencies accounting for 87% of the total energy. Wave  
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43 40 transformation is thus spatially variable and is strongly modulated by platform  
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45 41 elevation and the tidal range. While shore platforms in microtidal environments have  
46  
47 42 been shown to be highly dissipative, in this macro-tidal setting up to 90% of the  
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49 43 offshore wave energy reached the landward cliff at high tide, so that the shore  
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51 44 platform cliff is much more reflective.  
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56 **Key Words**  
7  
89 Shore platform, wave energy, wave transformation, infragravity, morphodynamics  
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1415 **Introduction**  
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18 Shore platforms are a conspicuous feature of rock coasts and are also found in  
19 lakes (Allan *et al.*, 2002; Trenhaile, 2004) and estuaries (Kennedy, 2010). Many  
20 questions over the formation of shore platforms and likely future impacts of climate  
21 change remain unanswered (Naylor *et al.*, 2010; Trenhaile, 2011, 2014a). The  
22 evolution of shore platforms is complicated by variable geological settings (geology,  
23 lithology, and tectonics), long development times (> 1000 years) and sea level  
24 changes where evolution over several glacial cycles is possible (Trenhaile 2014b).  
25 Consequently the age and rates of development of shore platforms and rock coasts  
26 is difficult to resolve; although recent modelling and the application of cosmogenic  
27 dating is improving this understanding (e.g. Choi *et al.*, 2012; Thébaudeau, *et al.*,  
28 2013; Hurst *et al.*, 2016). A holistic understanding of rock coast evolution is  
29 essential if we want to predict the resilience and vulnerability of rock coasts under  
30 changing climatic conditions.  
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48 Understanding wave transformation across shore platforms and its role in rock coast  
49 erosion is crucial to understanding the processes driving rock coast evolution. Field  
50 monitoring of wave hydrodynamics on shore platforms has been recently advanced  
51 by a number of studies investigating cross shore wave transformation and patterns  
52 of infragravity energy ( $f < 0.05$  Hz) on platforms (Stephenson and Kirk, 2000; Taylor,  
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3 68 2003; Farrell *et al.*, 2009; Marshall and Stephenson, 2011; Ogawa *et al.*, 2011;  
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5 69 Beetham and Kench, 2011; Ogawa *et al.*, 2012; Ogawa, 2013; Ogawa *et al.*, 2015;  
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7 70 Ogawa *et al.*, 2016; Brayne, 2016). To date, all of these instrumented studies of  
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10 71 wave transformation on shore platforms have occurred in micro- and mesotidal  
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12 72 (hereafter, microtidal) environments. Ogawa (2013) reported on how wave energy is  
13  
14 73 expended across a mesotidal shore platform. He reported a high degree of energy  
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16 74 dissipation across the platform and development of infragravity energy at the inner  
17  
18 75 platform. Only Trenhaile and Kanyaya (2007), Poate *et al.* 2016 and Brayne (2016)  
19  
20 76 have measured waves on platforms in macrotidal settings, however these studies did  
21  
22 77 not investigate energy in the infragravity frequency. Studies in microtidal settings  
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24 78 have revealed a variety of surf zone types including highly dissipative shore  
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26 79 platforms (Stephenson and Kirk, 2000; Ogawa *et al.*, 2012) and reflective shore  
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28 80 platforms mixed with dissipative morphologies (Marshall and Stephenson, 2011).  
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33 81 A key gap in our understanding is the fate of energy delivered to rock coasts and  
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35 82 in turn how this energy affects erosion and sediment dynamics. One approach  
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37 83 advocated by Stephenson and Thornton (2005); Dickson *et al.* (2007) and  
38  
39 84 Stephenson (2014) has been to adopt a morphodynamic framework similar to that  
40  
41 85 used in beach research. In these terms rock coast morphologies can be considered  
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43 86 reflective (e.g. plunging cliffs), intermediate (shore platforms with elements of  
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45 87 reflection and dissipation) and dissipative (e.g. very wide platforms in shallow water).  
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47 88 Work carried out thus far shows how tidal range, platform width, platform gradient  
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49 89 and consequently water depth over the platform play an important role in determining  
50  
51 90 the proportion of wave energy that is reflected and dissipated (Marshall and  
52  
53 91 Stephenson, 2011; Beetham and Kench, 2011; Ogawa, 2013; Earlie *et al.*, 2015;  
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55 92 Ogawa *et al.*, 2015). In microtidal environments wide platforms are highly dissipative  
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3 93 while narrow platforms are reflective at high tide. For microtidal platforms shallow  
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5 94 water depth at high tide means wave breaking dissipates significant amounts of  
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7 95 energy before reaching the landward margin of the platform where cliff retreat occurs  
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10 96 (Stephenson and Kirk, 2000). Here, waves are forced to break either before or at  
11  
12 97 the seaward edge of the platform. In the case of a macrotidal setting, wave energy  
13  
14 98 can be delivered much closer to the cliff at the back of the platform because water  
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16 99 depths are greater at high tide. It remains to be shown how much energy from  
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18 100 deepwater is expended at the cliff platform junction. In addition to examining the  
19  
20 101 transformation of wave energy, field investigations have shown the presence of  
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22 102 significant amounts of infragravity energy occur on dissipative microtidal platforms  
23  
24 103 but we are yet to demonstrate the (expected) presence of infragravity energy on  
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26 104 macrotidal platforms. Dickson *et al.* (2013) argued that infragravity energy is  
27  
28 105 important for the continual widening of horizontal platforms in microtidal  
29  
30 106 environments because infragravity energy increases water depth and allows more  
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32 107 incident wave (0.05-0.33 Hz) energy to reach the cliff foot enhancing wave erosion of  
33  
34 108 the cliff and aids seismic cliff shaking and weathering processes. They suggested  
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36 109 that continual widening negates the traditional model of steady state equilibrium  
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38 110 where microtidal platform widening rates decrease over time due to incident wave  
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40 111 attenuation across the widening platform. Thus, there are still important questions  
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42 112 requiring resolution about the presence and geomorphic role of infragravity energy  
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44 113 on rock coasts – especially in macrotidal settings with the least wave transformation  
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46 114 research to date.

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53 115 We present an instrumented field study of wave transformation across a  
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55 116 macrotidal shore platform. We asked:

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3 117 1. How are waves and energy expended across a shore platform where tidal  
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5 118 range is large (macrotidal)?  
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7 119 2. How much infragravity energy is present on a shore platform in a macrotidal  
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9 120 environment under low to moderate wave conditions?  
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11 121 3. What differences (if any) are there in wave transformation patterns between  
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13 122 this macrotidal site and the existing data on microtidal and mesotidal  
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15 123 platforms?  
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### 125 **Study Site**

126 The studied shore platform – cliff system is located between Nash Point and St  
127 Donat's, Wales, in the semi-diurnal macrotidal Bristol Channel with a neap to spring  
128 tidal range of 9 – 11 m tidal range (Figure 1) due to the resonance effects in the  
129 Bristol Channel. The site is exposed to Atlantic generated storm waves exceeding  
130 5.5 m, where mean annual significant wave height is approximately 2 to 2.5 m  
131 (Channel Coast Observatory, 2014). Shore platforms are developed in Blue Lias  
132 limestone, which is characterised by alternating thin bands of shale and thicker  
133 layers of limestone (Trueman, 1930). The platforms reach widths of up to 300 m  
134 although widths less than 200 m are more common. Platforms slope seaward at  
135 about three degrees and follow the geological dip of the Lias (Trenhaile, 1972),  
136 Platforms are backed by eroding cliffs up to 30 m high and the shore platform is  
137 eroded during extreme storms (Naylor et al., 2016). The rock mass properties of the  
138 Blue Lias limestone produce a platform surface which is typically comprised of wide  
139 (200 – 300 m) smooth platform surfaces that are broken by near vertical steps  
140 between bed layers (Stephenson and Naylor, 2011).

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3 141 Wave conditions in the region can be characterised using data from the  
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5 142 Scarweather wave monitoring buoy, located approximately 40km WNW of the study  
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7 143 site. The geographical orientation of the estuary means that waves approach the site  
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10 144 almost exclusively from a WSW direction (Figure 2), with the distribution of  
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12 145 significant wave height ( $H_s$ ) and mean zero-crossing period ( $T_z$ ) for 2009 as  
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14 146 illustrated in Figure 2.  
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## 148 **Methods**

### 149 *Field measurements*

150 Wave measurements were made using three self-contained wave and tide  
151 recorders (RBR-2050). The instruments were factory calibrated before deployment  
152 and operate with a <1% measurement error. The three RBR-2050s were deployed  
153 along a shore normal transect where the transducers were located at the upper  
154 platform (6 m from the cliff), middle platform (90 m from the cliff) and the outer  
155 platform. The outer recorder was 163 m from the cliff and 50 m from the low tide  
156 edge of the platform (Figure 3). We assume waves cross the platform shore normal  
157 to the shore following previously published examples (e.g. Trenhaile and Kanyaya,  
158 2007; Marshall and Stephenson, 2011; Ogawa et al., 2011, 2016); this assumption  
159 was validated using the SWAN wave model described below and accords with our  
160 observations during fieldwork . The platform profile was surveyed using a total  
161 station where elevations are reported relative to Ordnance Datum (i.e. mean sea  
162 level). In order to protect the pressure transducers from the potential impact of  
163 mobile boulders (e.g. Naylor *et al.*, 2016), 65 mm diameter holes were cored into the  
164 platform surface using a petrol powered rock corer. The resistant nature of the  
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3 165 limestone beds of the Blue Lias meant that the time to taken to core these holes  
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5 166 (over an hour each) prevented locating the most seaward recorder at the absolute  
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7 167 low tide level. Each pressure transducer was placed in the hole and weighed down  
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10 168 using lead dive weights so that the top of the transducer was flush with the platform  
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12 169 surface. The transducer sensors were thus at the level of the platform surface while  
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14 170 recording. They were programmed to record 2048 samples at a frequency of 4 Hz,  
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16 171 beginning at 10 minute intervals. This results in 8.53 minute bursts separated by  
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18 172 2.47 minutes with no sampling (Marshall and Stephenson, 2011). Wave  
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20 173 measurements on the platform were made over four days (12:00 hrs 08-04-2009 to  
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22 174 12:00 hrs 12-04-2009) capturing eight high tides during a spring tidal sequence. The  
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24 175 raw pressure record is converted to summary wave statistics for each burst using  
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26 176 software that supports the RBR-2050. The supporting software also compensates for  
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28 177 the depth decay of the pressure signal using known coefficients for different wave  
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30 178 frequencies, the depth of deployment and water depth (Gibbons *et al* 2005). Wave  
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32 179 energy was partitioned into four frequency bands: infragravity waves (< 0.05 Hz);  
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34 180 swell waves (0.05–0.125 Hz); wind waves (0.125–0.33 Hz); and capillary waves (>  
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36 181 0.33 Hz) following Ogawa *et al.* (2011; 2012; 2013; 2015). Changes in wave height,  
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38 182 degree of wave attenuation, and wave energy transformations on the platform were  
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40 183 assessed from summary wave statistics and power spectral analysis conducted  
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42 184 using Matlab® (Marshall and Stephenson, 2011).  
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48 185 Since our wave recorders did not measure direction of wave approach nor were  
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50 186 we able to deploy instruments off shore of the platform, we undertook wave  
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52 187 modelling over the deployment period using the Simulating WAVes Nearshore  
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54 188 (SWAN) model (Booij *et al.*, 1999). A coarse grid domain, with 0.01° resolution was  
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56 189 established over the area from 3 to 5.25° W and 50.25 to 51.75° N, using offshore  
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3 190 wave boundary conditions from the European Centre for Medium-range Weather  
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5 191 Forecasting (ECMWF). The offshore boundary conditions used to drive the model  
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7 192 are shown in Figure 2. Output from the coarse grid domain model produced  
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9  
10 193 boundary conditions for a high resolution ( $0.002^\circ$ ) nested grid domain covering the  
11  
12 194 Bristol Channel with a boundary at  $4.25^\circ$  W. SWAN was run in non-stationary mode  
13  
14 195 to allow a higher temporal resolution and more realistic sea state evolution. Wind  
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16 196 conditions were provided by ECMWF, and tidal heights and currents for the nested  
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18 197 model taken from predictions for Swansea, 27 km west of the study site. The model  
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21 198 was run from 5-15 April 2009, producing predictions for significant wave height,  $H_s$ ,  
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23 199 mean zero-crossing wave period,  $T_z$ , and direction at 30 minute intervals. The mean  
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25 200 zero-crossing period parameter  $T_z$  was used in preference to the mean period  
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27 201 parameter  $T_m$  to align with the data available from the wave monitoring buoys  
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29 202 detailed below.. The actual model output point is located approximately 1 km  
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31 203 offshore from the platform study site (Figure 1) to avoid modelling inaccuracies  
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33 204 associated with very shallow water at low tides. The model therefore generates wave  
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35 205 statistics at the study site before, during and after our field deployment (after Naylor  
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37 206 et al., 2016). The predicted sea states are a statistical representation of each 30  
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39 207 minute period, consequently there will be a significant number of larger individual  
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41 208 waves within each period.  
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46 209 Finally we supplemented our measured and modelled wave results with data  
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48 210 from the two nearest wave monitoring sites. The first, the Minehead buoy, which is  
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50 211 maintained by the Channel Coast Observatory (CCO, 2014) and is located at 10 m  
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52 212 water depth offshore from Minehead, on the opposite side of the Bristol Channel,  
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54 213 approximately 18 km from our study site. The second is the Scarweather buoy, part  
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56 214 of the Cefas WaveNet network of wave monitoring buoys (Cefas, 2016), located  
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3 215 approximately 40 km WNW of our study site at 35 m depth (Figure 1). Data from  
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5 216 both buoys are used to provide a broader environmental context for our measured  
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7 217 and modelled wave data, however, they are too close to the study site to provide  
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9 218 boundary data for the SWAN model. Data from the buoys are summarised in Figure  
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## 12 13 14 15 220 **Results**

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21 222 *Offshore Wave Measurements* Wave data for March and April 2009 from the  
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23 223 Bristol Channel are presented in Figure 2. Data from the Scarweather buoy provide  
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25 224 a better indication of the conditions at the platform because the buoy is fully exposed  
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27 225 to the southwesterly seas which impact on the study site, whereas the Minehead  
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29 226 buoy is in a more sheltered location. However, only significant wave heights and not  
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31 227 maximum wave heights are available for Scarweather; therefore a combination of  
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33 228 both the Minehead and Scarweather buoys were used to compare against our  
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35 229 platform wave data. A comparison of scatter plots for Scarweather buoy data for  
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37 230 2009 and the platform deployment period (Figure 2) confirms that the significant  
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39 231 wave heights experienced during the deployment are in line with the typical values  
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41 232 seen across the year. However, the wave periods during the deployment period are  
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43 233 notably higher than the average. Therefore although the wave energy levels  
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45 234 experienced during the deployment can be considered typical (since energy is  
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47 235 proportional to  $H_s^2$ ), the waves are more powerful than average (with wave power  
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49 236 additionally proportional to the wave period), with potential effects on breaking  
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51 237 characteristics. Overall, we can characterise the deployment period as having low to  
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53 238 moderate energy levels (with  $H_s$  in the range of 0.45 - 3.04m) relative to storm  
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3 239 significant wave heights that can exceed 5.6 m in the Bristol Channel (CCO, 2014).  
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5 240 Whilst it would have been desirable to measure a wider range of energy conditions,  
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7 241 limited field deployment time restricted the opportunity to capture a full range of wave  
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9 242 conditions. Consequently, our analysis is limited to eight high tides over 4 days/96  
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11 243 hours during low to moderate energy conditions, which are similar to those  
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13 244 measured in previous studies (Table 3). .  
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### 246 *Offshore Modelled Waves*

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248 Figure 4 illustrates SWAN output and is compared to the seaward wave  
249 recorded on the shore platform study site. Modelled wave heights ranged from 1.09  
250 m just before the deployment to 0.32 m just after the study period, and are strongly  
251 influenced by the tidal elevation in the region. During the transducer deployment  
252 offshore wave heights decreased. Modelled wave direction was typically between  
253 240 and 250 deg, i.e. from a WSW direction. This is in contrast to the wave  
254 directions of approximately 250-270 degrees seen at the Scarweather buoy (Figure  
255 3), illustrating the refraction that the waves are subject to as they approach the  
256 platform which leads to wave fronts breaking almost parallel to the cliff at high tide.  
257 The modelled wave conditions can be characterised as low energy compared with  
258 those recorded at the Scarweather buoy due to energy losses from nearshore  
259 interactions. In comparison to waves recorded on the outer edge of the platform,  
260 modelled wave heights were smaller, likely reflecting shoaling transformation of  
261 wave height as waves enter shallower water.

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6 263 *Incident Waves*

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9 264 Water level and wave heights ( $H_{\text{sig}}$  and  $H_{\text{max}}$ ) over the eight tides of the  
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11 265 deployment are displayed in Figure 5. Where data gaps occur these are during low  
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13 266 tides when the instruments were exposed. Over the period of deployment  $H_{\text{sig}}$   
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15 267 ranged from 1 to 1.43 m and  $H_{\text{max}}$  did not exceed 2.41 m (Table 4). This represents  
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17 268 non-storm conditions.

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21 269 At all recorders, over the entire deployment interval, the mean significant wave  
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23 270 period was nine seconds but ranged from 3.2 to 13 s. This wide range of wave  
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25 271 periods results from the occurrence of both wind and swell waves during the  
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27 272 deployment, with short period wind waves dominating the early and later part of the  
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29 273 wave record as the tide floods and ebbs over the platform (Figure. 5). Swell waves  
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31 274 generally dominated the middle of the wave record over each high tide, particularly  
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33 275 on the middle and outer part of the platform. Figure 6 illustrates a representative  
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35 276 example of one burst of data (8.5 minutes) from each of the three transducers at the  
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37 277 same time; wave groups are evident and can be clearly seen at the middle and outer  
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39 278 transducers.

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47 280 *Wave Transformation*

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50 281 The cross shore pattern of wave height ( $H_{\text{sig}}$ ) is illustrated in Figure 7. At the  
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52 282 peak of the high tide the largest significant ( $H_{\text{sig}}$ ) waves occurred across the inner  
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54 283 platform on seven of the eight high tides. Thus wave height tends to increase across  
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56 284 the platform as waves shoal and rise prior to breaking. However there was one  
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3 285 exception to this pattern, on 9 April, when a single  $H_{\max}$  wave recorded at the middle  
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5 286 transducer was measured at 2.41 m, 2 cm larger than the 2.39 m  $H_{\max}$  wave recorded  
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7 287 at the inner platform position in a synchronous burst. On two of the high tides waves  
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9 288 were of a similar height at all three recorders. Notably at high tide there was not a  
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11 289 pattern of decreasing wave heights across the platform; this is the opposite of what  
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13  
14 290 is commonly found on microtidal shore platforms (Marshall and Stephenson 2011;  
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16 291 Ogawa et al. 2016). This has important implications for the capacity of waves to  
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18 292 initiate rocky shore erosion (see discussion below). These data also show a strong  
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21 293 link between shore platform elevation and wave breaking, as breaking occurs during  
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23 294 high tide at the highest platform elevation in the cross shore gradient (Figure 3). The  
24  
25 295 same observation was made by Brayne (2016). Figure 8 illustrates wave energy on  
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27 296 the upper platform compared to the wave energy at the middle and outer recorders  
28  
29 297 over the instrument deployment. There is a general pattern of higher energy on the  
30  
31 298 inner platform: wave energy is 300% and 335% greater compared with the outer  
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33 299 platform and the middle platform, respectively.  
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37 300 A representative sample of power spectral density (PSD) plots are presented in  
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39 301 Figure 9. In this figure synchronous 8.53 minute bursts are plotted from three days  
40  
41 302 for two high tides and one mid tide situation. The arrows on Figure 5 (outer recorder  
42  
43 303 panel) indicate the timing of these three bursts. Figure 9 show PSD at a high tide on  
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45 304 the 8 and 9 April 2009 and at mid tide on 10 April 2009. On 8 April the PSD plots are  
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47 305 dominated by energy in the swell and wind wave frequencies. On the middle and  
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49 306 outer platform there is a dominance of swell (74% and 79% respectively), and wind  
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51 307 waves account for 25% and 20% of the energy respectively. Infragravity energy is  
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53 308 1.3% at the middle transducer and less than 1% at the outer transducer. On the  
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55 309 upper platform the transducer recorded more infra-gravity (i.e. 12.2% to 13.4% of the  
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3 310 total energy) but there is still a dominance of energy in the wind and swell  
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5 311 frequencies.  
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8 312 The pattern of energy spectra over the whole field campaign is illustrated in  
9  
10 313 Figure 10. The dominance of swell wave frequencies (around 0.1 Hz) is notable  
11  
12 314 where most energy is in the swell frequency band. Infragravity energy is noticeably  
13  
14 315 absent from the outer and middle platform, except for the small “tail” (see circle on  
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16 316 lower panel of Figure 10. as an example) as the tide rises across the platform. On  
17  
18 317 the upper recorder more infragravity energy is evident at high tide. These patterns  
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20 318 are indicative of the low energy conditions measured.  
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## 28 320 **Discussion**

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30 321 Our results clearly show that under low to moderate energy conditions wave  
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32 322 characteristics across this macrotidal shore platform are tidally modulated and are  
33  
34 323 influenced by variations in platform elevation. This result is consistent with previous  
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36 324 studies in microtidal (Stephenson and Kirk, 2000; Marshall and Stephenson, 2011;  
37  
38 325 Ogawa *et al.*, 2011; Ogawa *et al.*, 2012), mesotidal (Ogawa, 2013) and macrotidal  
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40 326 (Trenhaile and Kanyaya, 2007; Brayne, 2016; Poate *et al.*, 2016) settings. However  
41  
42 327 the pattern of wave energy dissipation and reflection across the macrotidal platform  
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44 328 measured here differs from that of previous studies.  
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## 52 330 *Cross Platform Transformation*

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55 331 Under low to moderate energy conditions we found that similar sized or larger  
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57 332 waves occurred on the inner platform at high tide compared to the middle and outer  
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3 333 platform. On the macrotidal shore platform reported here, deep water depths (~8 m)  
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5 334 at high tide allows waves to cross the platform with relatively little change in wave  
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7 335 height due to shoaling, where they break close to the cliff platform junction. The  
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9 336 exact position of the high tide breaking point will depend on the ratio of wave height  
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11 337 to water depth, which is modulated by platform elevation (Brayne, 2016). During our  
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13 338 study, high tide wave breaking was limited to within 6 m of the cliff-platform junction  
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15 339 (assuming  $H/h = 0.73$ ). Thus the high tide surf zone is restricted to a narrow zone  
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17 340 (e.g. 5-6% of platform width for a 1 m wave) on the inner part of the platform, where  
18  
19 341 width of the surf zone is a function of water depth, platform elevation and wave  
20  
21 342 height. When waves are less than 2 m at high tide, 90% of the platform is crossed by  
22  
23 343 waves before breaking can occur. The surf zone occupies ~ 10% of the platform at  
24  
25 344 high tide where the outer edge of the shore platform is only important around low tide  
26  
27 345 when wave energy is focussed here. Using tidal inundation data (Figure. 5) we  
28  
29 346 calculated that this window is approximately 30 minutes in duration on each flood  
30  
31 347 and ebb tide (~ 60 minutes per tidal cycle). At high tide water depths across the  
32  
33 348 much of the platform are too great for moderate waves to break and consequently  
34  
35 349 there is little opportunity for waves to cause meso-scale platform erosion (cobble and  
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37 350 boulder sized erosion products, e.g. Naylor *et al.*, 2012) and boulder transport  
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39 351 (Naylor *et al.*, 2016). Consequently, this platform is likely to have a more reflective  
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41 352 morphology than that of dissipative platforms, since high tide wave energy is  
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43 353 expended in a relatively narrow zone on the upper part of the platform close to the  
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45 354 reflective cliff (or steep boulder beaches where these occur).  
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53 355 While we have not measured waves during storm events, it can be expected that  
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55 356 larger storm waves will create a wider surfzone, where the entire width of the surf  
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57 357 zone will enlarge over the shore platform as the tides ebb and flow. Data on  
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3 358 platform erosion and boulder transport from Naylor et al. (2016) confirms this, as  
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5 359 platform erosion and boulder transport occurred across the mid and upper intertidal  
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7 360 zone during storm conditions. There will be some dissipation across the platform but  
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9  
10 361 it is likely far greater amounts of wave energy will be able to reach the upper part of  
11  
12 362 the platform and the landward cliff than we measured under low to moderate wave  
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14 363 climate.  
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### 20 365 *Wave Height and Water Depth*

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23 366 Only two previous investigations of wave breaking on shore platforms have  
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25 367 compared the surf zone wave height and water depth ratio commonly applied to  
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27 368 beaches. Farrell *et al.* (2009) using  $H_{rms}$ , showed that the wave breaking height on a  
28  
29 369 shore platform in Portugal was 42% of the water depth, which is similar for wave  
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31 370 breaking in the surf zone of sandy beaches (Thornton and Guza, 1982). Ogawa *et al.*  
32  
33 371 (2011) demonstrated  $H_{max}$  was limited to 0.7 water depth ( $h$ ) and  $H_{sig}$  was 0.4  $h$ . This  
34  
35 372 relationship generally held across the platform although there was some variability  
36  
37 373 on the seaward edge. Figure 11 shows the pattern of wave height and water depth  
38  
39 374 across the Glamorgan platform by plotting  $H_{sig}$  and  $H_{max}$  against water depth. On the  
40  
41 375 inner platform wave height is controlled by water depth (which is in turn modulated  
42  
43 376 by platform elevation) with  $H_{sig}$  approximately 0.74  $h$ . Using Pearson's correlation,  
44  
45 377 the relationship is significant at 0.000. At the middle platform  $R^2 = 0.14$  and  
46  
47 378 significant at 0.000. While at the outer platform  $R^2 = 0.13$  and significant at 0.000.  
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49 379 These low  $R^2$  values are expected given that for much of the time particularly during  
50  
51 380 mid to high tide, water depths are too great to force breaking.  $H_{max}$  at the upper  
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53 381 platform  $R^2 = 0.78$  and is significant at 0.000.  $H_{max}$  at the mid platform site  $R^2 = 0.12$   
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3 382 and is significant at 0.000. At the outer platform the  $R^2$  value was 0.07 and also  
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5 383 significant at 0.000. Results such as these are consistent with Trenhaile and  
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7 384 Kanyaya (2007) and the low values for the middle and outer platform are as a result  
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10 385 of water depths being far greater than wave height over the peak of the high tide.  
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12 386 Thus wave breaking is a function of water depth determined by the level of tidal  
13  
14 387 inundation and platform elevation which was also observed by Brayne (2016) on  
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16 388 macrotidal shore platforms. Similar to Ogawa *et al.* (2011) there is a degree of  
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18 389 scatter around the best fit line for the inner platform wave recording site. We  
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21 390 attribute this to the variable water depths and small wave heights.  
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### 26 392 *Infragravity Energy*

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30 393 Our field data unsurprisingly confirms the presence of infragravity energy on a  
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32 394 macrotidal shore platform. At high tide in microtidal settings wave breaking releases  
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34 395 infragravity energy on the outer edge of platforms and is found across the platform  
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36 396 increasing shorewards (Marshall and Stephenson, 2011; Beetham and Kench, 2011;  
37  
38 397 Ogawa *et al.*, 2011, Ogawa *et al.*, 2012, Ogawa, 2013). On the macrotidal platform in  
39  
40 398 this study, high tide wave breaking was confined to the upper part of the platform;  
41  
42 399 here wave breaking occurs more as a function of water depth rather than  
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44 400 topography. Under higher energy conditions and a wider surf zone there would be  
45  
46 401 an increase in the amount of infragravity energy available across a greater width of  
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48 402 the platform. Under low-moderate energy conditions infragravity energy was  
49  
50 403 insignificant across the platform with less than 12 to 13% of the total energy reaching  
51  
52 404 the upper platform being in the infragravity band compared with 85% measured by  
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54 405 Ogawa *et al.* (2012). Taylor (2003) noted that gravity energy was “lost” to the  
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3 406 infragravity band on platforms on the Kaikoura Peninsula in New Zealand and so not  
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5 407 available for geomorphic work. More recent consideration of the role of infragravity  
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7 408 energy suggests that the energy is still able to drive geomorphic change (Dickson *et*  
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9 409 *al.*, 2013). Such a low percentage of energy in the infragravity band at Glamorgan  
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11 410 does mean more energy is in the gravity wave frequency. Regardless of the types of  
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13 411 waves, the low to moderate energy conditions measured during this study are  
14  
15 412 unlikely to have much, if any, erosive consequence. Whether infragravity energy is  
16  
17 413 available for meso scale (i.e. cm – m) erosion and sediment transport requires more  
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19 414 field investigations coupling wave, erosion and transport data under higher energy  
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21 415 conditions. While there is still much uncertainty as to the geomorphic significance of  
22  
23 416 infragravity energy on rock coast erosion (Ogawa *et al.*, 2011; Dickson *et al.*, 2013) it  
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25 417 appears that it has little, if any role under low-moderate energy conditions in this  
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27 418 macrotidal setting.  
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32  
33 419 Some authors have speculated that infragravity energy may facilitate platform  
34  
35 420 abrasion when infragravity energy acts to re-suspend abrasive sediments (Beetham  
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37 421 and Kench, 2011; Marshall and Stephenson, 2011; Ogawa *et al.*, 2012; Ogawa,  
38  
39 422 2013). However such a scenario requires suitably sized sediment to be available. At  
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41 423 this site loose large cobbles and fine to medium sized boulders and are the dominant  
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43 424 sediment classes available on the platform (Naylor and Stephenson, 2010) and it is  
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45 425 unlikely that water level changes associated with infragravity energy would be able to  
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47 426 suspend such large sediment particles.  
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#### 51 427 *Comparisons to previous wave transformation research*

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54 428 Our findings demonstrate that wave transformation across macrotidal shore  
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56 429 platforms has fundamental differences with those measured under similar energy  
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3 430 conditions on micro to mesotidal shore platforms (Table 3). Crucially, they show that  
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5 431 macrotidal shore platforms are reflective, with narrow energy windows within which  
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7 432 geomorphic work can take place, where wave heights are greatest at high-tide, at  
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9 433 the cliff-platform junction. This is the opposite of what happens on microtidal  
10  
11 434 platforms (Table 3). This finding has important implications for rock coast evolution  
12  
13 435 models and erosion predictions for macrotidal shore platforms and associated cliffs,  
14  
15 436 particularly as storminess and sea levels increase. An important consequence of  
16  
17 437 the macrotidal setting is that the outer margins and seaward edge of the platform  
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19 438 becomes hydrodynamically disconnected from the surf zone at mid to high tide and  
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21 439 becomes part of the subtidal offshore profile. As the ebbing tide floods the platform  
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23 440 (i.e. the surf zone moves landward) the increasing water depth over the lower to mid-  
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25 441 tidal sections means direct wave influences are reduced and wave breaking moves  
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27 442 landward. On microtidal platforms relatively shallow water depths at high tide (< 1.5  
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29 443 m) mean that the surf zone influences much more of the platform where the outer  
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31 444 platform is still exposed to wave forces and currents that are capable of eroding the  
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33 445 platform and transporting debris.  
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## 447 **Conclusions**

448 In this macrotidal setting, waves are transformed across the study platform  
449 differently to those on platforms in microtidal settings where most previous wave  
450 transformation research has taken place. Rather than a reduction in wave height  
451 across the shore platform (as is the case in microtidal settings), waves remain the  
452 same or increase in height from the outer seaward edge to the inner margin. This  
453 pattern occurs because water depth is greater than the breaking criterion for wave

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3 454 heights recorded in this study, consequently wave transformation is tidally  
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5 455 modulated. The highest wave energies were recorded at the cliff-platform junction  
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7 456 where ~90% of the remaining platform is effectively sub-tidal at high tide. Active  
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9 457 wave erosion of the platform is thus most likely limited to a narrow window of  
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11 458 opportunity as the tide floods and ebbs over the platform and only when wave  
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13 459 heights are large enough to quarry and entrain the boulder sized erosion products  
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15 460 (Stephenson and Naylor, 2011; Naylor *et al.*, 2016). Thus wave erosion of shore  
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17 461 platforms is closely tethered to suitable energy windows which narrows and  
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19 462 concentrates the time period when shore platforms and cliffs are likely to be eroded  
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21 463 by waves. Further field data, including wave measurements coupled with high  
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23 464 resolution boulder erosion and boulder transport monitoring data, are required to  
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25 465 validate this assumption.  
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41 471 work.  
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3 601 LIST OF FIGURES AND TABLES  
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9 603 Figure 1. Location of study site and wave array across a sloping macrotidal shore  
10 platform on the Glamorgan coast, Wales, UK. Note SWAN model output located 1  
11 604 km from the low tide edge of the shore platform.  
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19 607 Figure 2. Wave data from Minehead and Scarweather Buoys march to April 2009.  
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21 608 Box indicates period of deployment of wave recorders on the study shore platform.  
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27 610 Figure 3. Cross shore profile of study platform showing location of the three wave  
28 recorders used in this study where platform elevation falls between stations was as  
29 611 follows: Inner – Middle (4.2 m ), Inner – Outer (6.59 m ), Middle – Outer (2.39 m ).  
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37 614 Figure 4 Comparisons of SWAN wave height output with most seaward pressure  
38 transduce deployed on shore platform.  
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45 617 Figure 5. Wave heights ( $H_{sig}$  and  $H_{max}$ ) and water depth across the shore platform  
46 over the wave recorder deployment period. Arrows indicate sample bursts shown in  
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49 619 Figure 6.  
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3 620 Figure 6 Example of a synchronous burst samples at 12:00 hrs 08-04-2009 showing  
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5 621 the water surface at each transducer. Wave groups are evident at the outer (c) and  
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7 622 middle (b) wave recorders.  
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13 624 Figure 7. Cross platform variations in  $H_{sig}$ . Note slightly higher waves in the inner part  
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15 625 of the platform compared to the middle and outer platform on six of the eight high  
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17 626 tides.  
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24 628 Figure 8 Comparison of wave energy across the shore platform. Wave energy on  
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26 629 the upper platform was calculated as a percentage of wave energy of the middle and  
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28 630 outer platform.  
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34 632 Figure 9. Power spectral density plots at a high tide on the 8 and 9 April 2009 and at  
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36 633 mid tide on 10 April 2009. The upper transducer was not inundated so there are no  
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38 634 data for 10 April at this time stamp. Note the increased presence of infragravity  
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40 635 energy on the middle and inner platform.  
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47 637 Figure. 10. Summary PSD plots for complete field deployment. Note wider plots for  
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49 638 inner recorder at infragravity frequencies and thin tails of infragravity energy at  
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51 639 middle and outer wave recorders (example denoted by ellipses).  
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3 641 Figure 11. Wave heights ( $H_{sig}$  and  $H_{max}$ ) plotted against water depth at each wave  
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5 642 recorder position across the platform.  
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11 644 Table 1 Annual  $H_{sig}$  exceedance and annual maximum  $H_{sig}$  2007 to 2011, Minehead  
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13 645 wave recorder (CCO, 2014).  
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19 647 Table 2. Annual  $H_{sig}$  exceedance and annual maximum  $H_{sig}$  2007 to 2011,  
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21 648 Scarweather wave recorder (CCO, 2014).  
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28 650 Table 3. Synthesis of existing wave transformation data across shore platforms ( $H_{sig}$   
29  
30 651 = significant wave height;  $H_{max}$  = maximum wave height; PT = pressure transducer;  
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32 652 ADC = Acoustic Doppler current meter; ECM = Electromagnetic current meter).  
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38 654 Table 4. Summary wave statistics, water level and pressure transduce locations.  
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665 Table 1.

Year	Annual $H_{sig}$ exceedance* (m)						Annual Maximum ( $A_{max}$ ) = $H_{sig}$		
	0.05%	0.50%	1%	2%	5%	10%	Date	$A_{max}$	(m)
2007	2.36	2	1.84	1.67	1.38	1.09	2-Dec-07	21:00	2.55
2008	2.7	2.17	2.01	1.78	1.5	1.27	10-Mar-08	23:00	2.77
2009	2.13	1.81	1.65	1.5	1.23	1.02	14-Nov-09	16:30	2.53
2010	2.36	1.66	1.47	1.29	1.03	0.84	31-Mar-10	10:00	2.68
2011	2.33	1.98	1.85	1.66	1.36	1.12	15-Dec-11	4:30	2.51

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677 Table 2

Year	Annual $H_{sig}$ exceedance (m)						Annual Maximum ( $A_{max}$ ) = $H_{sig}$		
	0.05%	0.50%	1%	2%	5%	10%	Date		$A_{max}$ (m)
2007	5.12	4.25	3.83	3.46	2.98	2.45	11-Jan-07	11:00	5.49
2008	4.89	3.8	3.53	3.28	2.82	2.41	10-Mar-08	20:00	5.43
2009 <sup>1</sup>	4.72	3.8	3.53	3.16	2.82	2.32	14-Nov-09	11:30	4.89
2010 <sup>1</sup>	5.26	3.08	2.80	2.53	2.16	1.77	11-Nov-10	23:00	5.61
2011	4.40	3.69	3.47	3.23	2.80	2.41	15-Dec-11	03:00	4.79

678 <sup>1</sup>There is a gap in the dataset from 27/11/09 – 31/3/10. Note that data from 2007 and 2010-11 are  
679 post-processed following download from the buoy and quality control procedures, and are of a  
680 higher quality than the telemetry data used for 2008 and 2009. There appears to have been a  
681 problem with the post-processing which means that only telemetry data are available for the full  
682 length of these years. The telemetry data has been processed into bins of  $H_{sig}$  for transmission,  
683 hence the repeat values in the exceedance data. The accuracy is therefore slightly lower, but the  
684 trends in the data are correct. These data are sourced from the Cefas WaveNet database  
685 (<https://www.cefas.co.uk/cefas-data-hub/wavenet/>).

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693 Table 3.

Author	Tidal Range	Platform width	Study Duration (hours)	H <sub>sig</sub> (m)	H <sub>max</sub> (m)	Location	Method	Size of Array
Stephenson and Kirk, (2000)	Micro	85-88	96	0.2-0.5	1.1	NZ	PT	4
Taylor, (2003)	Micro	85	60	0.2-0.5	0.3-0.7	NZ	ADCP ECM	1 2
Stephenson and Thornton (2005)	Micro	30	96	0.17-0.80		Australia	PT	2
Trenhaile and Kayana, (2007)	Meso Macro	100-180	96	0.25-0.85		Canada	Video camera and Poles	10 poles
Farrell <i>et al.</i> (2009)	Meso	70	40		0.92-1.14	Portugal	PT	7
Marshall and Stephenson (2011)	Micro	58 61 66 138	2×144	0-0.74		NZ & Australia	PT	3-5
Beetham and Kench (2011)	Micro	130 270	36	< 0.8		NZ	PT	5
Ogawa (2011)	Micro	250	24	0.4 - 0.6 m	0.86	NZ	PT	4
Ogawa <i>et al.</i> (2012)	Micro	140	24	0.5 - 0.6 m		NZ	PT	5
Ogawa (2013)	Meso	81	24	0.72 - 1.18		NZ	PT	5
Poate <i>et al.</i> (2016)	Macro					UK	PT	15
THIS PAPER	Macro	~200 m.	96	1.43	2.41	Wales, UK	PT	3

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700 Table 4.

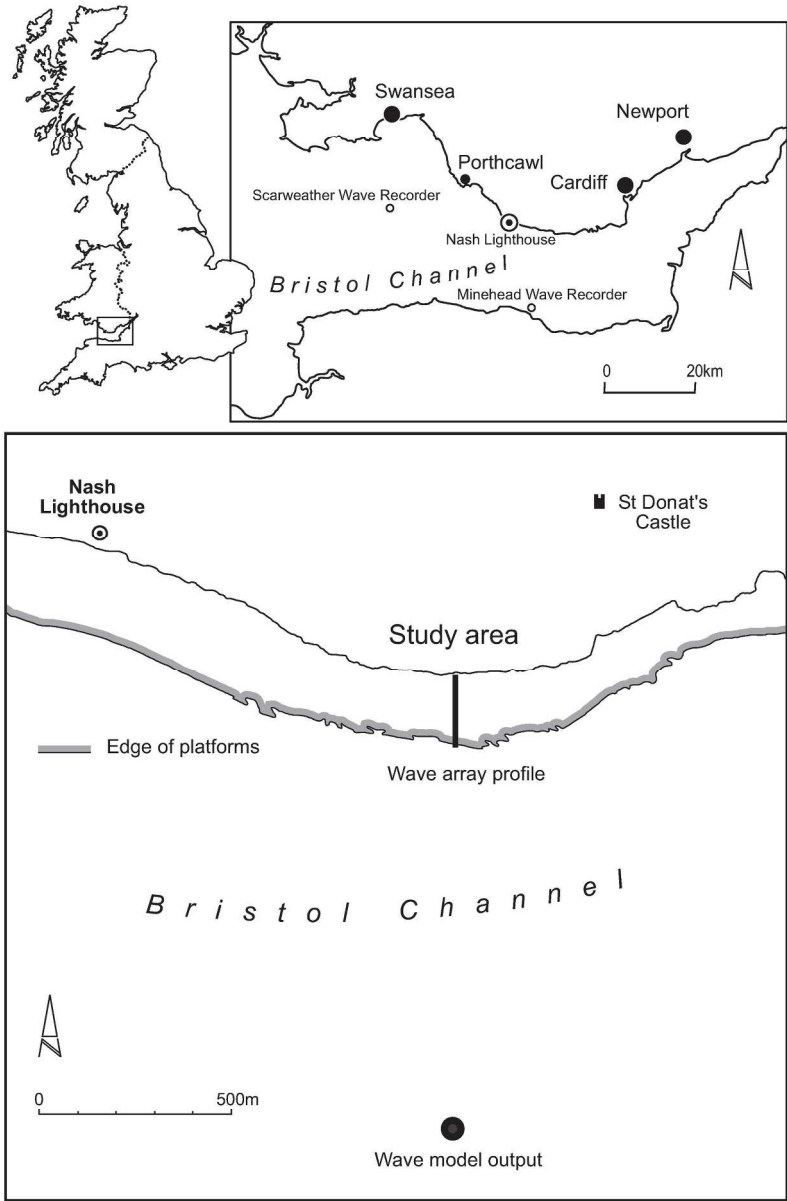
PT Location	Distance from cliff (m)	Shore Platform Elevation (m relative to MSL)	Hours of inundation over 4 days	$T_{sig}$	Largest $H_{sig}$ (m)	Maximum high tide water depth (m)	Largest $H_{max}$ at high tide	
							$H_{max}$	Date
Inner	6 m	5.85	26	5.0	1.43	1.55 m	2.39 m	8 April
Middle	90	1.64	52	9.0	1.35 m	5.7 m	2.41 m	9 April
Outer	163 m	-0.75	75	9.0	1.42 m	8.15 m	2.22 m	10 April

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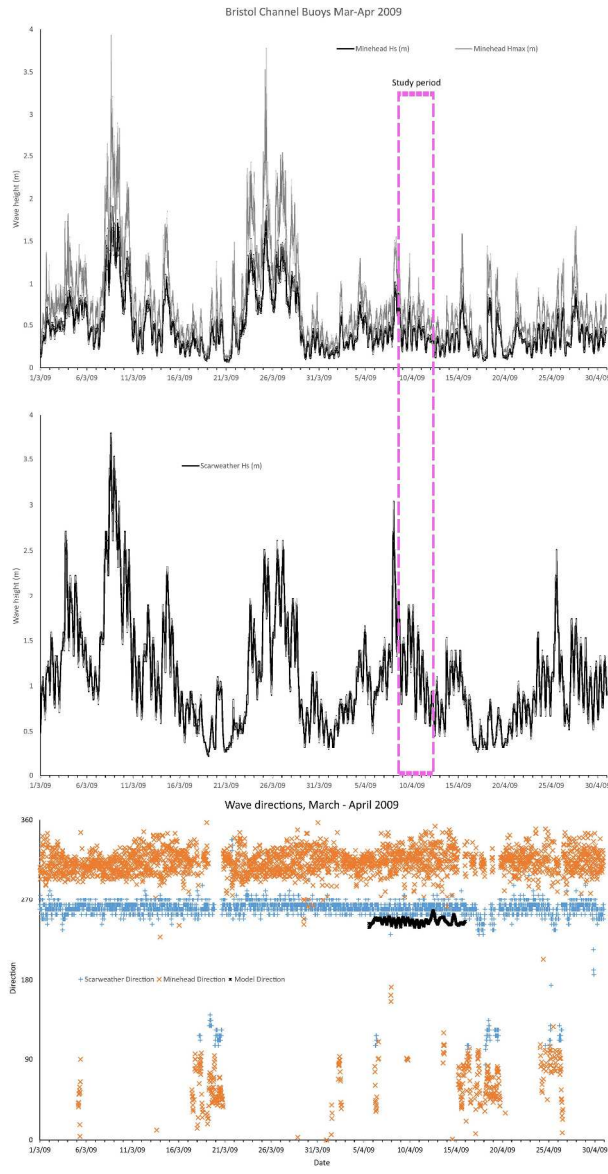
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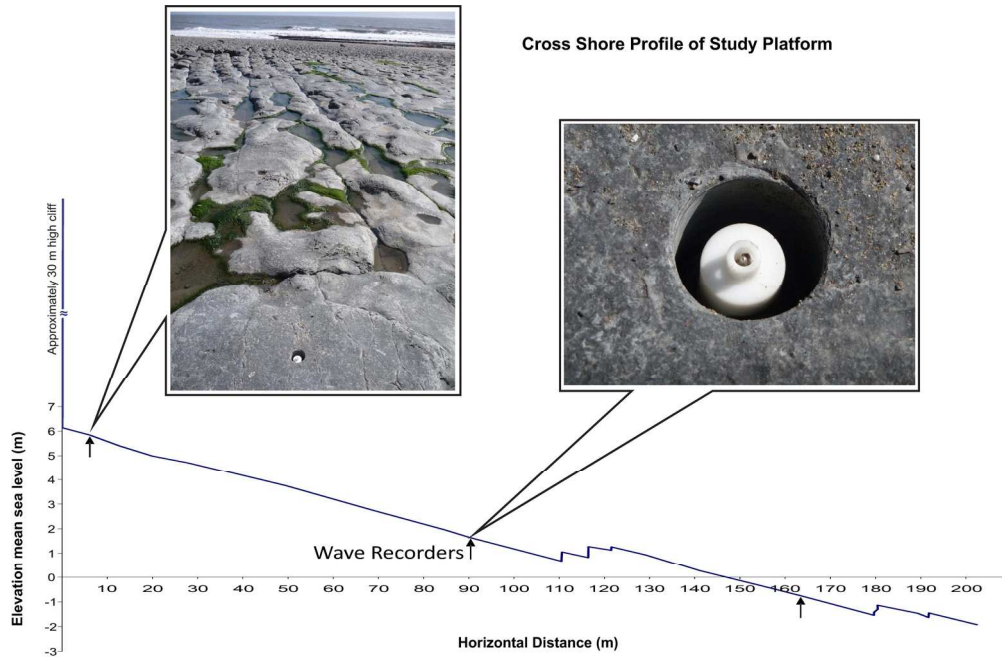


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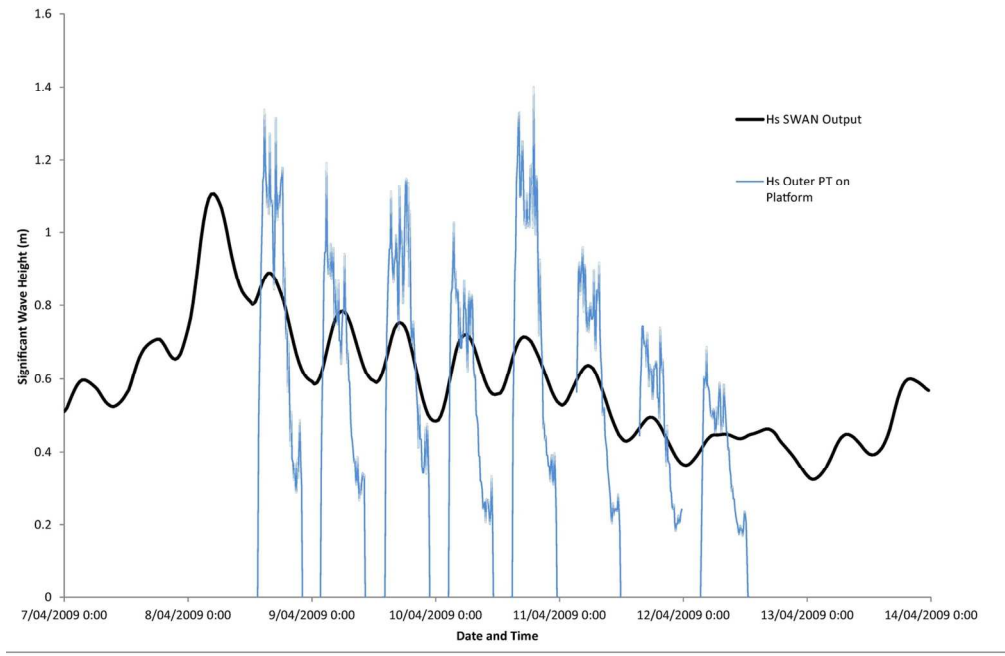


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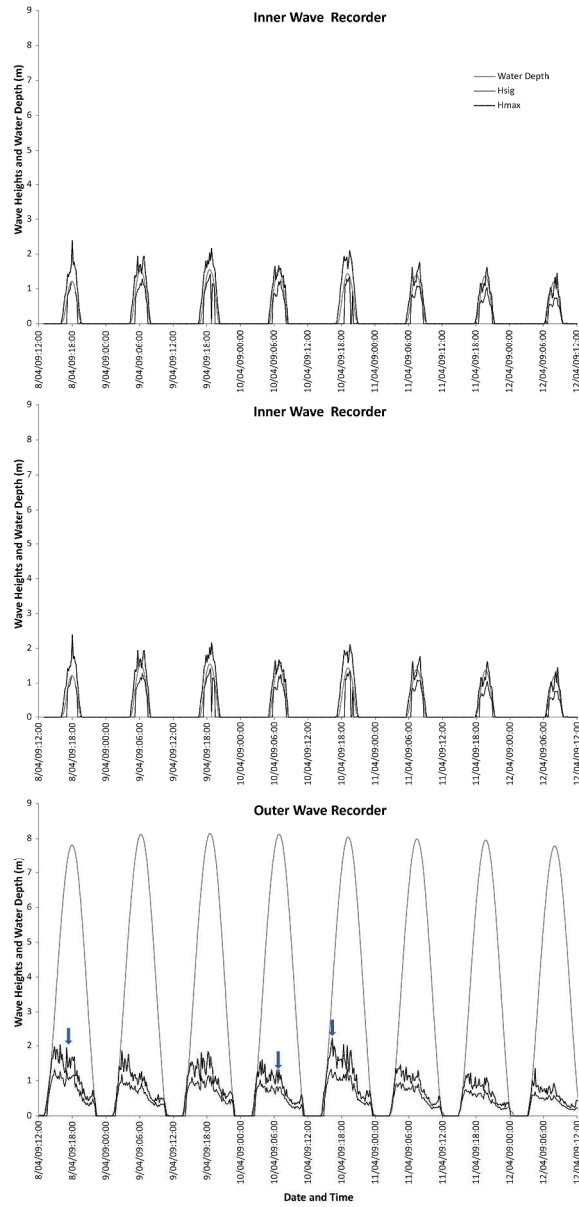
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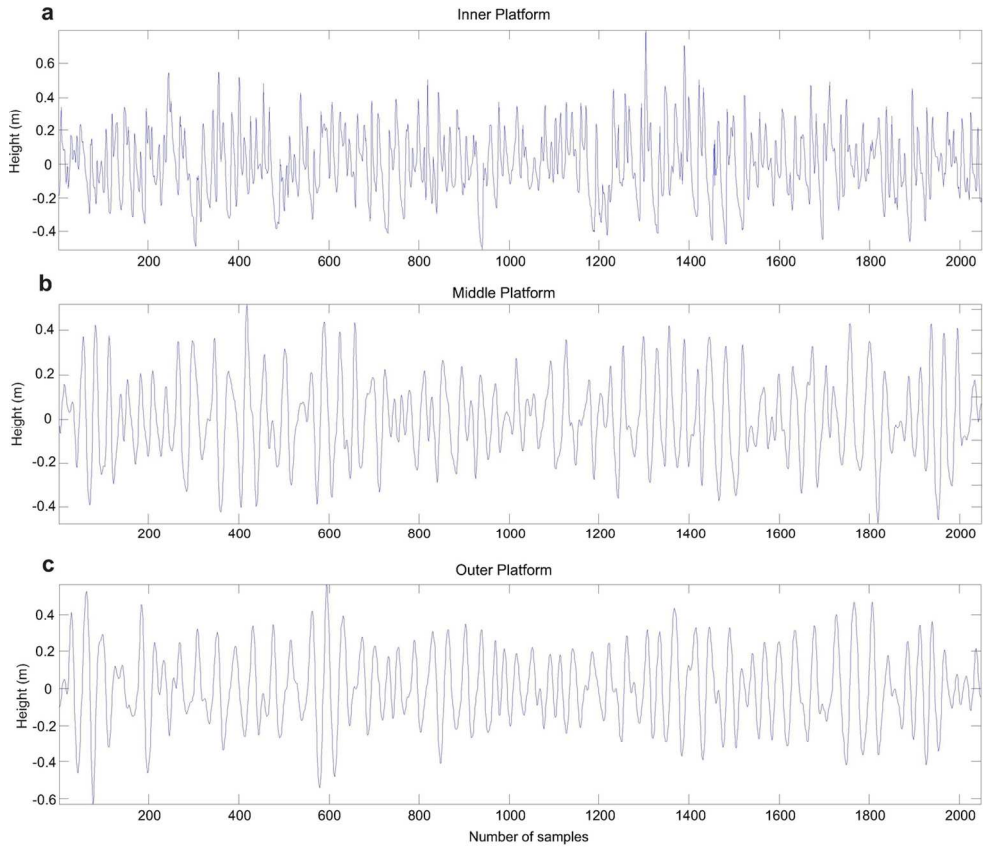
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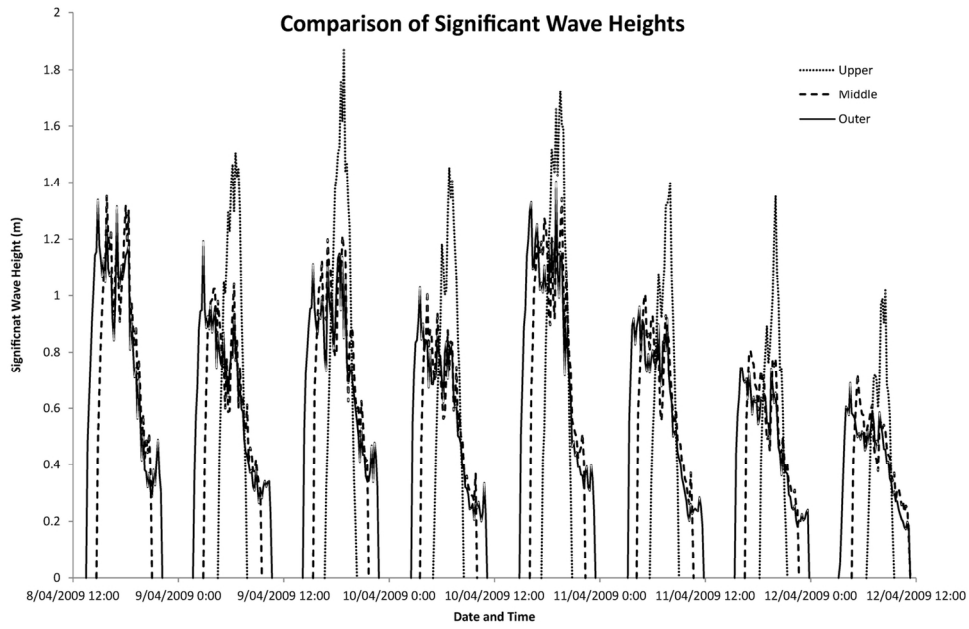
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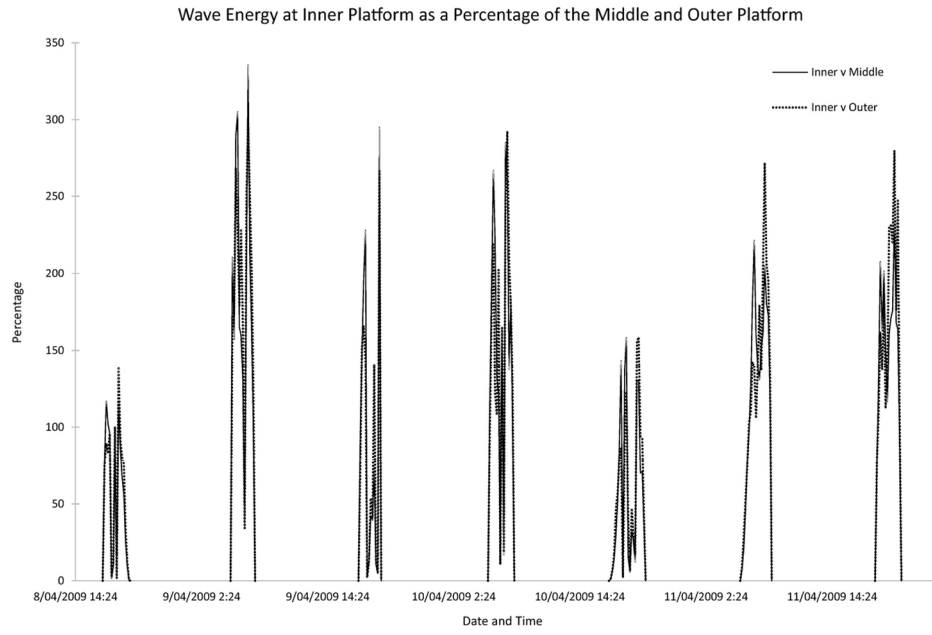
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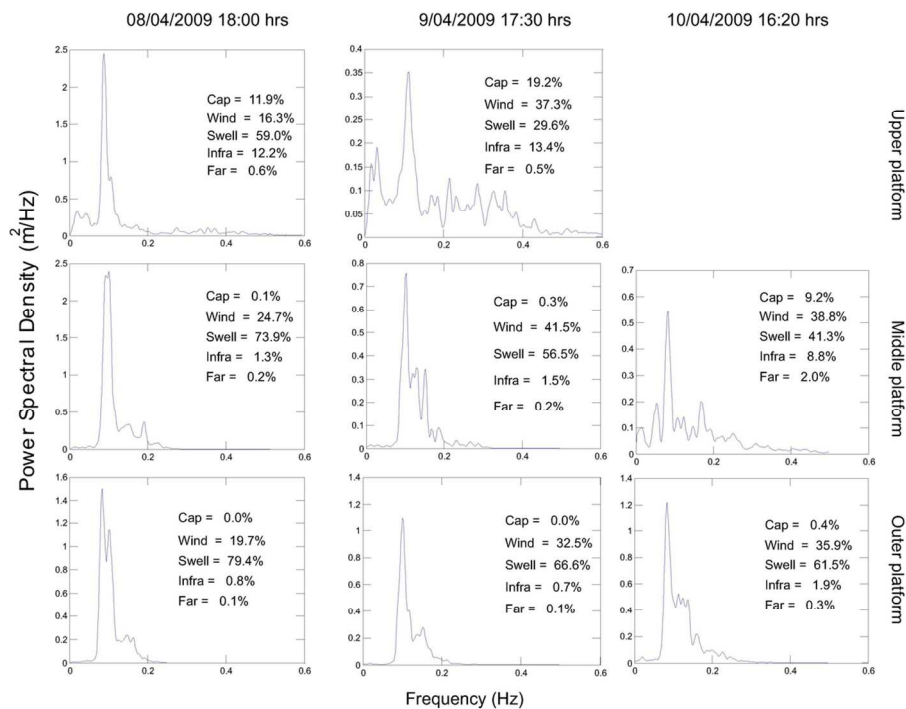
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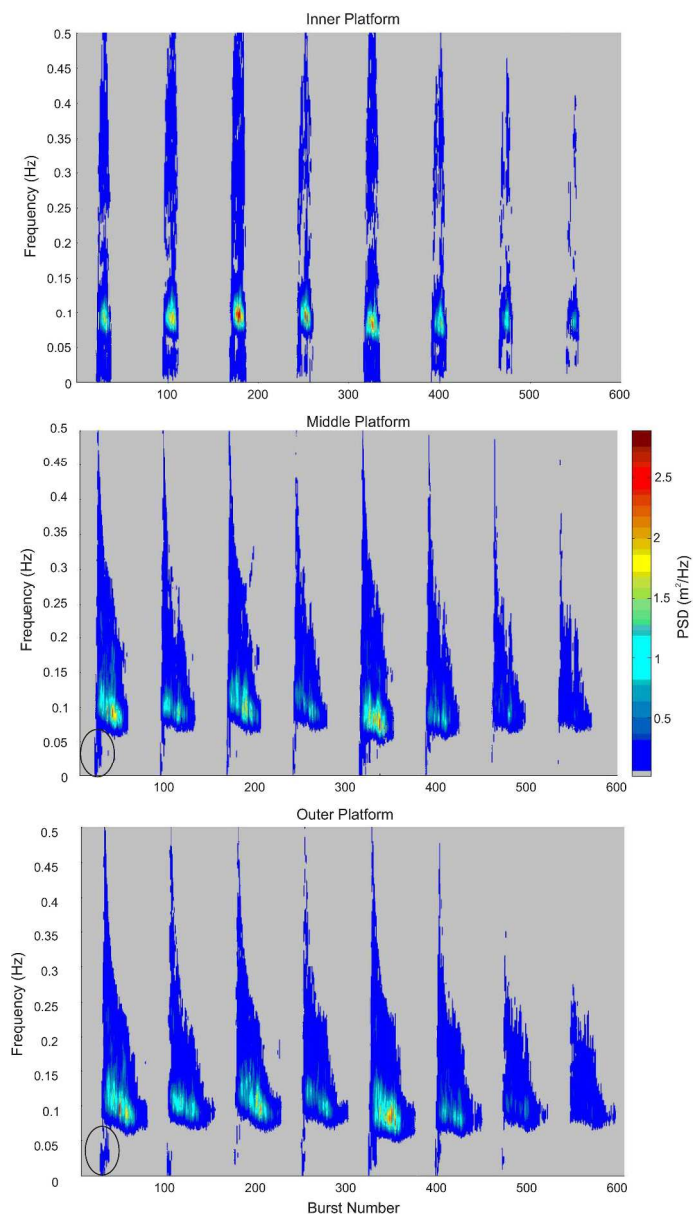


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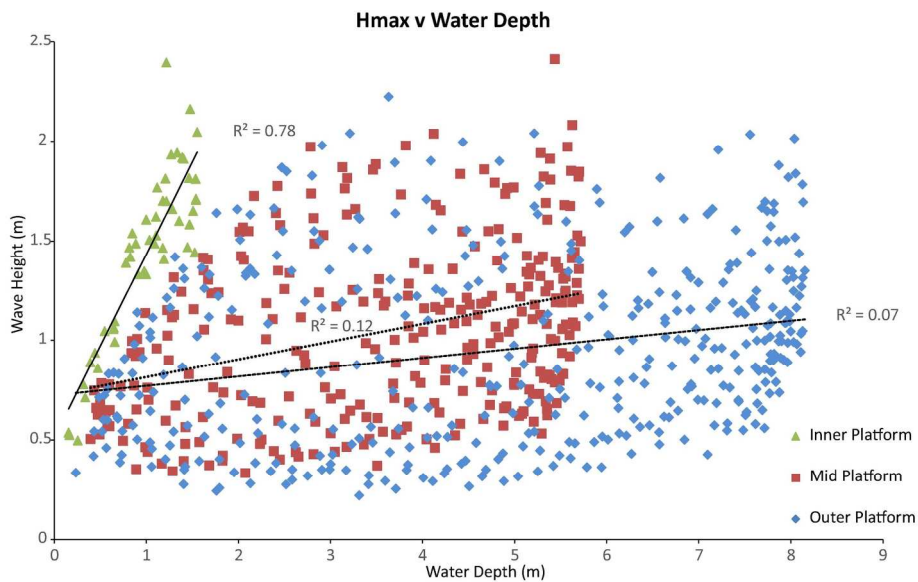
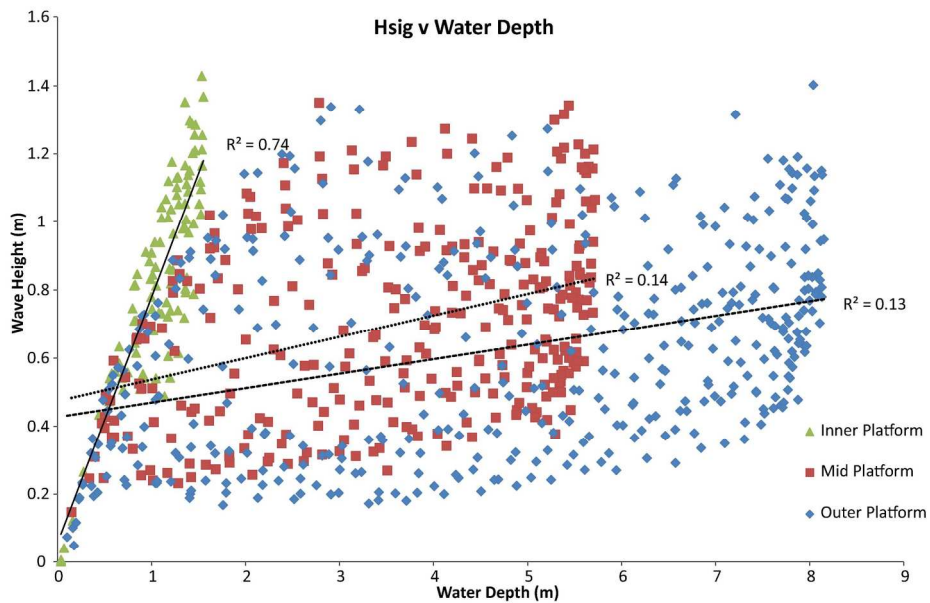
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3 **Wave Transformation across a macrotidal shore platform under low to moderate energy**  
4 **conditions**  
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8 Wayne J. Stephenson<sup>\*</sup>, Larissa A. Naylor, Helen Smith, Bin Chen, Ralph P. Brayne.  
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12 We investigate how waves are transformed across a shore platform as this is a  
13 central question in rock coast geomorphology. In this macro-tidal setting, under the  
14 wave conditions measured, up to 90% of the offshore wave energy reached the  
15 landward cliff at high tide, so that the shore platform cliff is highly reflective. At high  
16 tide inner platform wave heights were generally larger than near the seaward edge  
17 and infragravity energy was less than 13% of the total energy spectra.  
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