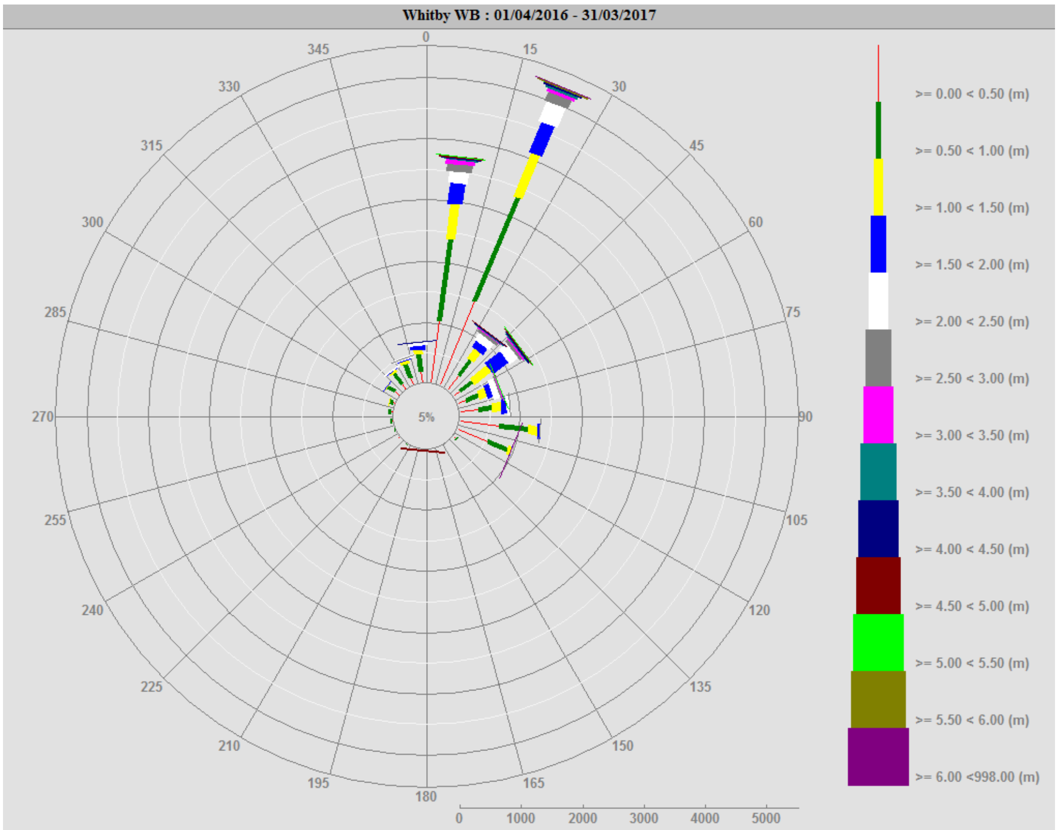


Wave Rose for Whitby Wave Buoy 2016-17

# Cell 1 Regional Coastal Monitoring Programme
# Wave & Tide Data Analysis Report 5: 2016 - 2017

**June 2017**

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Data and reports collected as part of the Cell 1 Regional Coastal Monitoring Programme are available to download via the North East Coastal Observatory via the webpage: www.northeastcoastalobservatory.org.uk.

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This study uses sea level monitoring data for Whitby and North Shields from the National Tide and Sea Level Facility, provided by the British Oceanographic Data Centre and funded by the Environment Agency.

Some of the wave data presented and analysed in this report has been obtained from the Cefas WaveNet site (http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/wavenet.aspx) and are subject to the Cefas data usage license as described on the next page.

## Abbreviations and Acronyms

| Acronym / Abbreviation | Definition |
|---|---|
| AONB | Area of Outstanding Natural Beauty |
| CD | Chart Datum |
| DGM | Digital Ground Model |
| EA | Environment Agency |
| HAT | Highest Astronomical Tide |
| LAT | Lowest Astronomical Tide |
| MHWN | Mean High Water Neap |
| MHWS | Mean High Water Spring |
| MLWN | Mean Low Water Neap |
| MLWS | Mean Low Water Spring |
| NOC | National Oceanography Centre |
| NTSLF | National Tide and Sea Level Facility |
| m | metres |
| OD | Ordnance Datum |
| PSMSL | Permanent Service for Mean Sea Level |
| WB | Wave Buoy |
| WMO | World Meteorological Organisation |

## Glossary of Terms

| Term | Definition |
|---|---|
| Beach nourishment | Artificial process of replenishing a beach with material from another source. |
| Berm crest | Ridge of sand or gravel deposited by wave action on the shore just above the normal high water mark. |
| Breaker zone | Area in the sea where the waves break. |
| Coastal squeeze | The reduction in habitat area which can arise if the natural landward migration of a habitat under sea level rise is prevented by the fixing of the high water mark, e.g. a sea wall. |
| Downdrift | Direction of alongshore movement of beach materials. |
| Ebb-tide | The falling tide, part of the tidal cycle between high water and the next low water. |
| Fetch | Length of water over which a given wind has blown that determines the size of the waves produced. |
| Flood-tide | Rising tide, part of the tidal cycle between low water and the next high water. |
| Foreshore | Zone between the high water and low water marks, also known as the intertidal zone. |
| Geomorphology | The branch of physical geography/geology which deals with the form of the Earth, the general configuration of its surface, the distribution of the land, water, etc. |
| Groyne | Shore protection structure built perpendicular to the shore; designed to trap sediment. |
| Mean High Water (MHW) | The average of all high waters observed over a sufficiently long period. |
| Mean Low Water (MLW) | The average of all low waters observed over a sufficiently long period. |
| Mean Sea Level (MSL) | Average height of the sea surface over a 19-year period. |
| Offshore zone | Extends from the low water mark to a water depth of about 15 m and is permanently covered with water. |
| Storm surge | A rise in the sea surface on an open coast, resulting from a storm. |
| Swell | Waves that have travelled out of the area in which they were generated. |
| Tidal prism | The volume of water within the estuary between the level of high and low tide, typically taken for mean spring tides. |
| Tide | Periodic rising and falling of large bodies of water resulting from the gravitational attraction of the moon and sun acting on the rotating earth. |
| Topography | Configuration of a surface including its relief and the position of its natural and man-made features. |
| Transgression | The landward movement of the shoreline in response to a rise in relative sea level. |
| Updrift | Direction opposite to the predominant movement of longshore transport. |
| Wave direction | Direction from which a wave approaches. |
| Wave refraction | Process by which the direction of approach of a wave changes as it moves into shallow water. |

## Preamble

The Cell 1 Regional Coastal Monitoring Programme covers approximately 300km of the north east coastline, from the Scottish Border (just south of St. Abb's Head) to Flamborough Head in East Yorkshire. This coastline is often referred to as 'Coastal Sediment Cell 1' in England and Wales (Figure 0.1). Within this frontage the coastal landforms vary considerably, comprising low-lying tidal flats with fringing salt marshes, hard rock cliffs that are mantled with glacial sediment to varying thicknesses, softer rock cliffs and extensive landslide complexes.

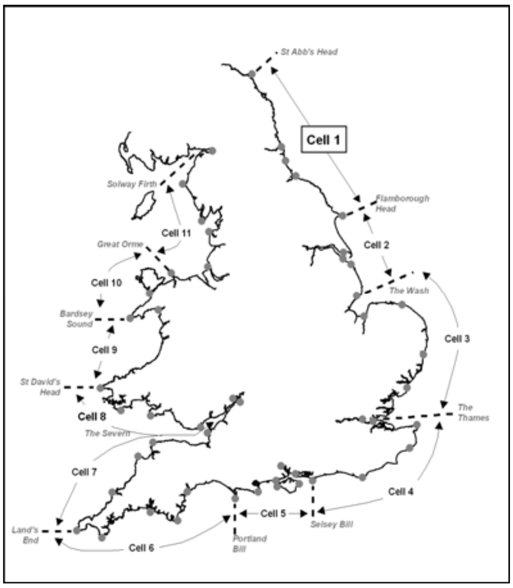



***Figure 0.1 Sediment Cells in England and Wales***

The work commenced with a three-year monitoring programme in September 2008 that was managed by Scarborough Borough Council on behalf of the North East Coastal Group. This initial phase has been followed by a five-year programme of work, which started in October 2011. The work is funded by the Environment Agency, working in partnership with the following organisations:

The main elements of the Cell 1 Regional Coastal Monitoring Programme involve:

- beach profile surveys
- topographic surveys
- cliff top recession surveys
- real-time wave data collection
- bathymetric and sea bed characterisation surveys
- aerial photography
- walk-over surveys

The beach profile surveys, topographic surveys and cliff top recession surveys are undertaken as a 'Full Measures' survey in autumn/early winter every year. Some of these surveys are then repeated the following spring as part of a 'Partial Measures' survey.

Each year, an Analytical Report is produced for each individual authority, providing a detailed analysis and interpretation of the 'Full Measures' surveys. This is followed by a brief Update Report for each individual authority, providing ongoing findings from the 'Partial Measures' surveys.

In addition, separate reports are produced for other elements of the programme as and when specific components are undertaken, such as wave data collection, bathymetric and sea bed sediment data collection, aerial photography, and walk-over visual inspections.

The present report is **Wave & Tide Data Analysis Report 5.** This provides an update to the analysis presented in the baseline wave and tide data report and compares the wave data collected between March 2016 and March 2017, to the baseline analysis in Wave & Tide Data Analysis Report 1 published in 2013 and updates in Wave & Tide Data Analysis Reports 2, 3, and 4.

# 1. Introduction

## 1.1. Study background and scope

Wave data collection is an integral part of the Cell 1 Regional Coastal Monitoring programme. Under the present programme data collection commenced in June 2010 when two Waverider buoys were deployed at Whitby and Newbiggin Ness in May 2010 by Cefas. These two buoys were decommissioned in June and November 2011 respectively.

Under the current phase of the programme, three new Waverider buoys have been deployed. These are located offshore from Scarborough, Whitby and Newbiggin Ness. The data from these new buoys has been disseminated in near real time on the Cell 1 Regional Coastal Monitoring programme and Channel Coast Observatory websites:

www.northeastcoastalobservatory.org.uk
http://www.channelcoast.org/
http://www.coastalmonitoring.org/

The data can also be downloaded from the Cefas website:
http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/wavenet.aspx.

Additionally, under the programme the existing tide gauge at Scarborough has been serviced and linked up to record concurrent water level data and a new tide gauge was deployed at Whitby.

The present report is **Wave & Tide Data Analysis Report 5** and provides an analysis of the wave and tide data collected during 2016-2017 as part of the programme. The report forms an update to and supersedes the baseline assessment in **Wave & Tide Data Analysis Report 1 (Halcrow, 2013),** and the update **Wave & Tide Data Analysis Reports 2 (Halcrow, 2014), 3 (CH2M, 2015), and 4 (CH2M, 2016)**. It also takes into consideration other freely available data collected in the region, in particular the Cefas WaveNet Tyne Tees offshore wave buoy; tide gauge data from Whitby and Scarborough collected under the programme; tide gauge data from North Shields and Whitby collected by NTSLF and ground level monitoring data from the University of Nottingham. The purpose of the report is to update and extend the analysis undertaken in the previous reports and inform the assessment and interpretation of other data collected under the programme such as the beach, cliff and coastal defence monitoring.

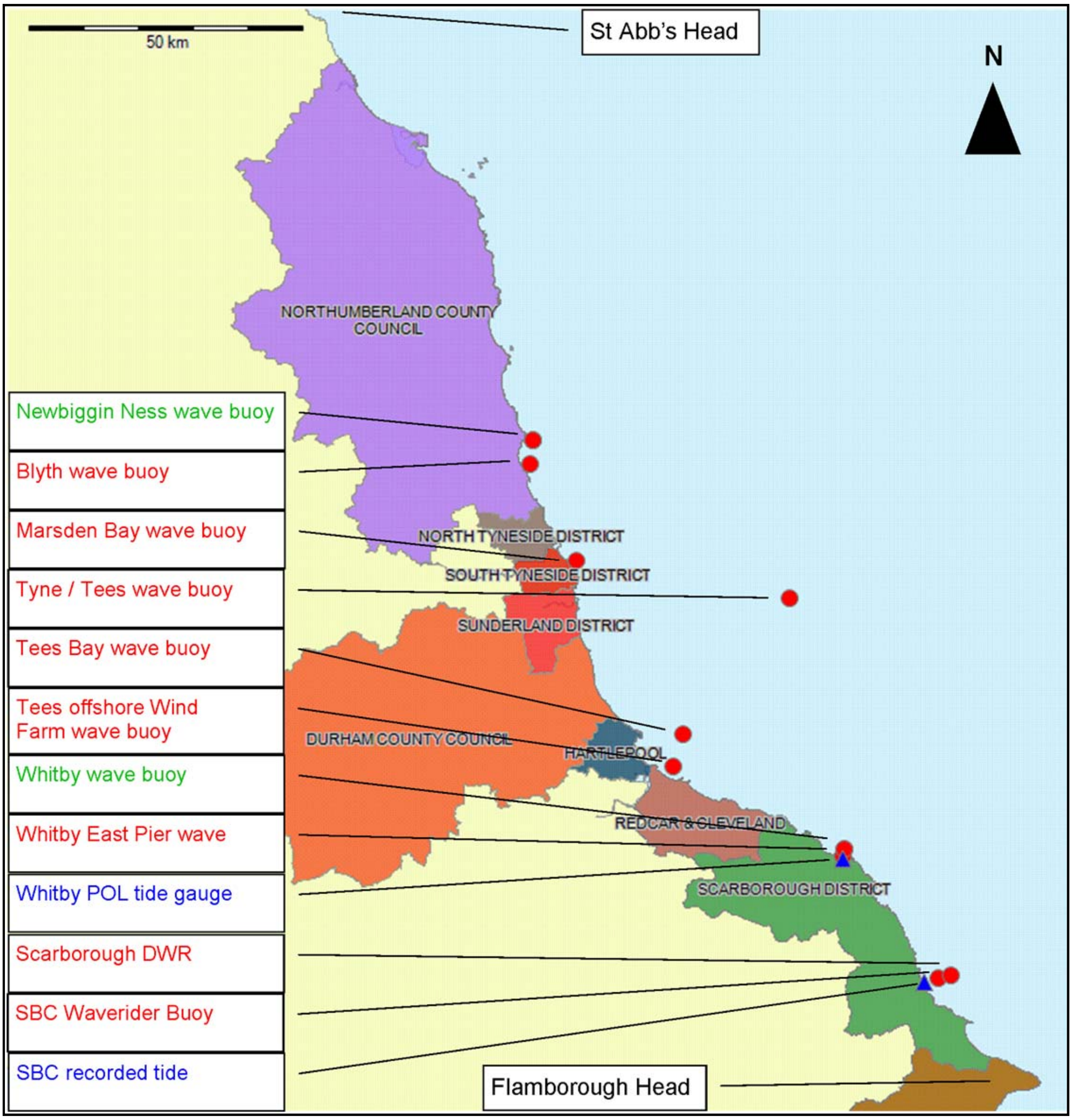
## 1.2. Study area and available wave and tide data

The Cell 1 study area extends along the northeast coast of England, from the Scottish border through to Flamborough Head. The baseline report, **Halcrow (2013)** considered the data at each location shown in
Figure 1.1.

In accordance with the recommendations in the baseline report this update report concentrates on the following locations, progressing from North to South along the coastline:

- Newbiggin wave buoy (Cell 1 programme),
- South Shields NTSLF Class A Tide gauge (NOC, formerly POL),
- Tyne Tees wave buoy (Cefas / WaveNet),
- Whitby wave buoy (Cell 1 programme),
- Whitby NTSLF Class A Tide gauge (NOC, formerly POL),
- Whitby Harbour tide gauge (Cell 1 programme),
- Scarborough wave buoy (Cell 1 programme),
- Scarborough tide gauge (Cell 1 programme).

These locations are shown in Figure 1.2 and more detailed location maps are shown in Appendix A.




Note: green text denotes the wave buoys that were installed by Cefas within the Cell 1 programme.

***Figure 1.1 Study Area and historical data sets reviewed in the baseline report (Halcrow 2013)***

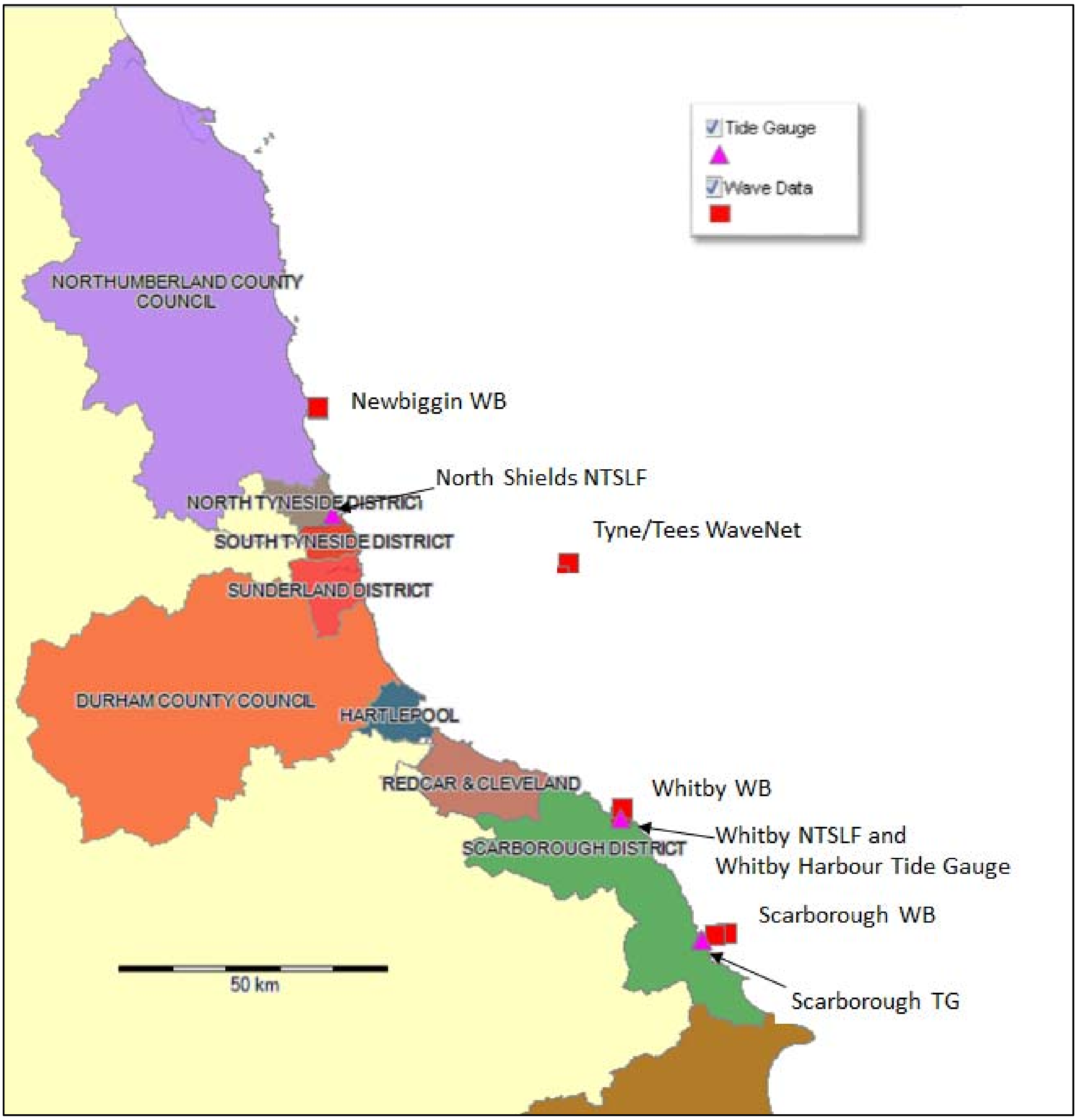



***Figure 1.2 Updated data sets reviewed in this report***

## 1.3. Methodology

The wave data received from the deployments at Newbiggin Ness, Whitby and Scarborough were imported into the Shoreline And Nearshore Data System (SANDS) database set up for the Cell 1 Regional Monitoring project for analysis and comparison with other datasets from the adjacent coastline. The data sets were reviewed in SANDS to check for any errors, inconsistencies or omissions.

Detailed graphs of the records of significant wave height, maximum wave height, mean and peak period, peak direction and water temperature for the Newbiggin Ness, Whitby and Scarborough wave buoy locations can be found in Appendices B, C and D respectively. These graphs were received from the Channel Coast observatory (CCO) with the monthly data. Detailed plots of the tide gauge data and the 2016 report on analysis of the Scarborough and Whitby tide gauge data by the CCO are provided in Appendix E.

It was identified in the baseline report that it was important to consider the Cefas WaveNet Tyne Tees offshore wave buoy as this is the longest consistent record offshore of the project area (deployed in December 2006). Data was therefore downloaded from the Cefas website http://cefasmapping.defra.gov.uk/Map and loaded into SANDS for comparison.

The following wave analyses were carried out:

- Wave roses were produced from the wave height and direction data at each location;
- Scatter tables of peak period and wave height were generated at each location; and
- Storm analyses were undertaken at each location.

The data from March 2016 to March 2017 were compared to the previous data. Note that the analysis has included data available up to the end of March 2017 in order to cover the full winter 2016 to 2017 period.

The water level monitoring data from the Scarborough and Whitby tide gauges managed by Fugro-Emu for Scarborough BC were also added into SANDS for analysis. The tide gauge deployed at Whitby under the programme originally had operational problems and this is now the second time it has been included in the annual report. Data from the Class A national tide gauges maintained by NTSLF at Whitby and North Shields were also downloaded and added to SANDS for inclusion in the analysis as was also done for the previous reports (CH2M, 2015 and 2016).

## 1.4. Summary of new data available

The new data sets considered in this report for comparison to the baseline data are listed in Table 1-1 below.

***Table 1-1 List of updated datasets available for the 2016 to 2017 report***

| Name of Location | Type of Data | Approx. Water depth (m) | Start Time | End Time |
|---|---|---|---|---|
| Newbiggin Ness WB | Wave Data | 23m | 01/04/2015 (deployed 21/06/2013) | ongoing |
| North Shields NTSLF Tide Record | Tidal Levels | N/A | 01/03/2015 (deployed 24/01/1946) | ongoing |
| Tyne Tees WaveNet Site (WMO ID 62293) | Wave Data | 65m | 01/04/2015 (deployed 07/12/2006) | ongoing |
| Whitby WB | Wave Data | 17m | 01/04/2015 (deployed 17/01/2013 | ongoing |
| Whitby Harbour TG | Tidal Levels | N/A | 01/04/2015 (deployed 08/05/2013 | ongoing |
| Whitby NTSLF Tide Record | Tidal Levels | N/A | 01/04/2015 (deployed 01/01/1991) | ongoing |
| Scarborough WB2* | Wave Data | 19m and 30m | 01/04/2015 (deployed 17/01/2013) | ongoing |
| Scarborough TG | Tidal Levels | N/A | 01/01/2015 (deployed 28/04/2003) | ongoing |

* Note that the location of the Scarborough WB was changed in June 2013. Data from the latter, further offshore location are designated as Scarborough WB2 in this report

# 2. Analysis of data

This section considers the data collected under the Cell 1 monitoring programme (i.e. the three wave buoys deployed by Fugro-EMU at Newbiggin Ness, Whitby and Scarborough respectively). It also reviews the longer term record for the Tyne Tees Cefas buoy and tide gauge data available from North Shields, Whitby and Scarborough.

## 2.1. Newbiggin Ness Waverider Buoy

The wave data in the baseline report for Newbiggin Ness was collected by the Cefas wave buoy deployed under the Cell 1 monitoring programme and published on the Cefas website. The baseline data set was just over 1 year and runs from 20/05/2010 to 07/06/2011.

Under the present phase of the programme the Newbiggin Ness wave buoy was deployed by Fugro-Emu on 21/06/2013 in the same location as in 2010-11.

Detailed monthly plots of the data collected during 2016-2017 are presented in Appendix B.

The new data set for 2016-2017 has been compared to the baseline data using scatter plots and tables produced in SANDS using the time series data analysis facilities.

### 2.1.1. Wave Height vs Peak Period

The Newbiggin wave height and zero crossing period data has been plotted on a scatter plot in Figure 2.1. Different symbols have been used to distinguish the baseline data from 2010/11 and different years of the current deployment. As the data sets are quite short no definitive conclusions can be drawn yet. The wave height / period relationships in Figure 2.1 appear similar. The largest measured wave heights to date were in the 2015/16 data. The wave heights over 5m in the latest data are from the November 21$^{st}$/22$^{nd}$ storm. The longest period waves occurred in December 2016 to January 2017, with only those recorded in 2014/15 being longer.

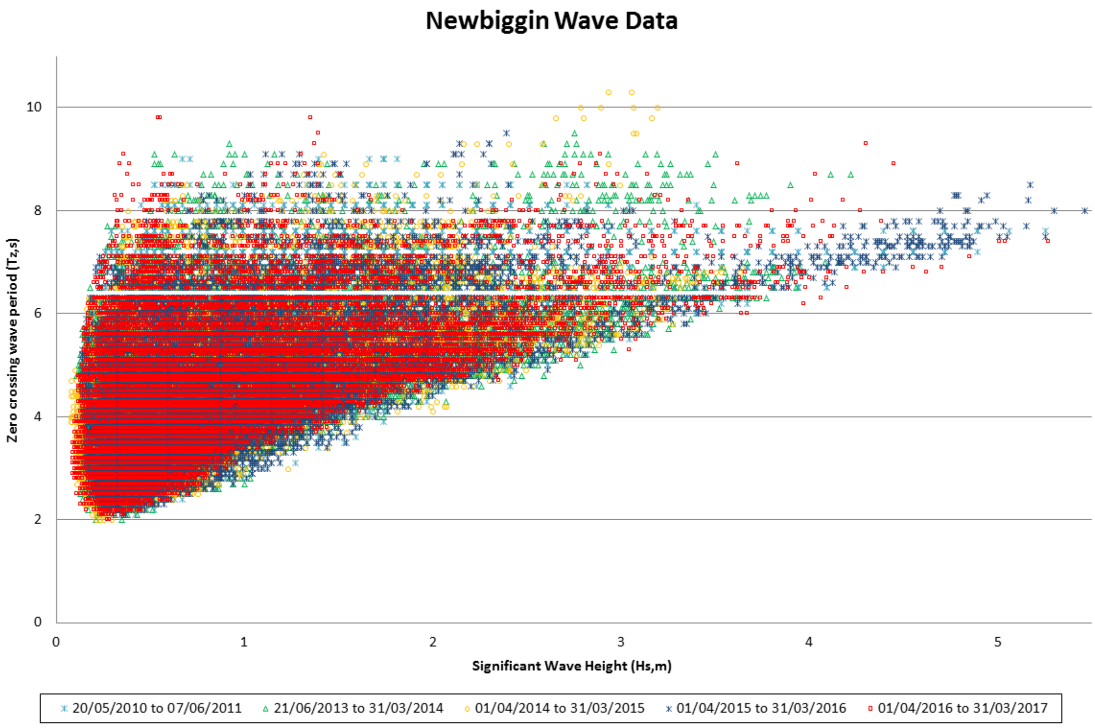



*Figure 2.1 Scatter plot of Wave Height Vs Peak Period at Newbiggin wave buoy*

### 2.1.2. Wave Rose

Wave roses showing wave height distribution by direction are shown in

Figure 2.2. The original deployment in 2010/11 (upper left diagram) shows that the waves predominantly approach the Newbiggin Ness wave buoy from the Northeast (30 to 60 degrees). The data from the current deployment has been plotted in yearly April to March blocks, all of which show the main direction to be the north east, but also a significant proportion of waves from the southeast. It could be that 2010/11 had fewer storms from the south east than usual, or there could be an issue with the 2010/11 data set. However, a much longer data set of at least ten years would be required to assess how representative the five wave roses are and the annual variability in storms.

Comparing the baseline wave roses in
Figure 2.2 to the other locations analysed (see Figure 4.1) indicates that the Newbiggin Ness site is relatively sheltered from waves from the north.

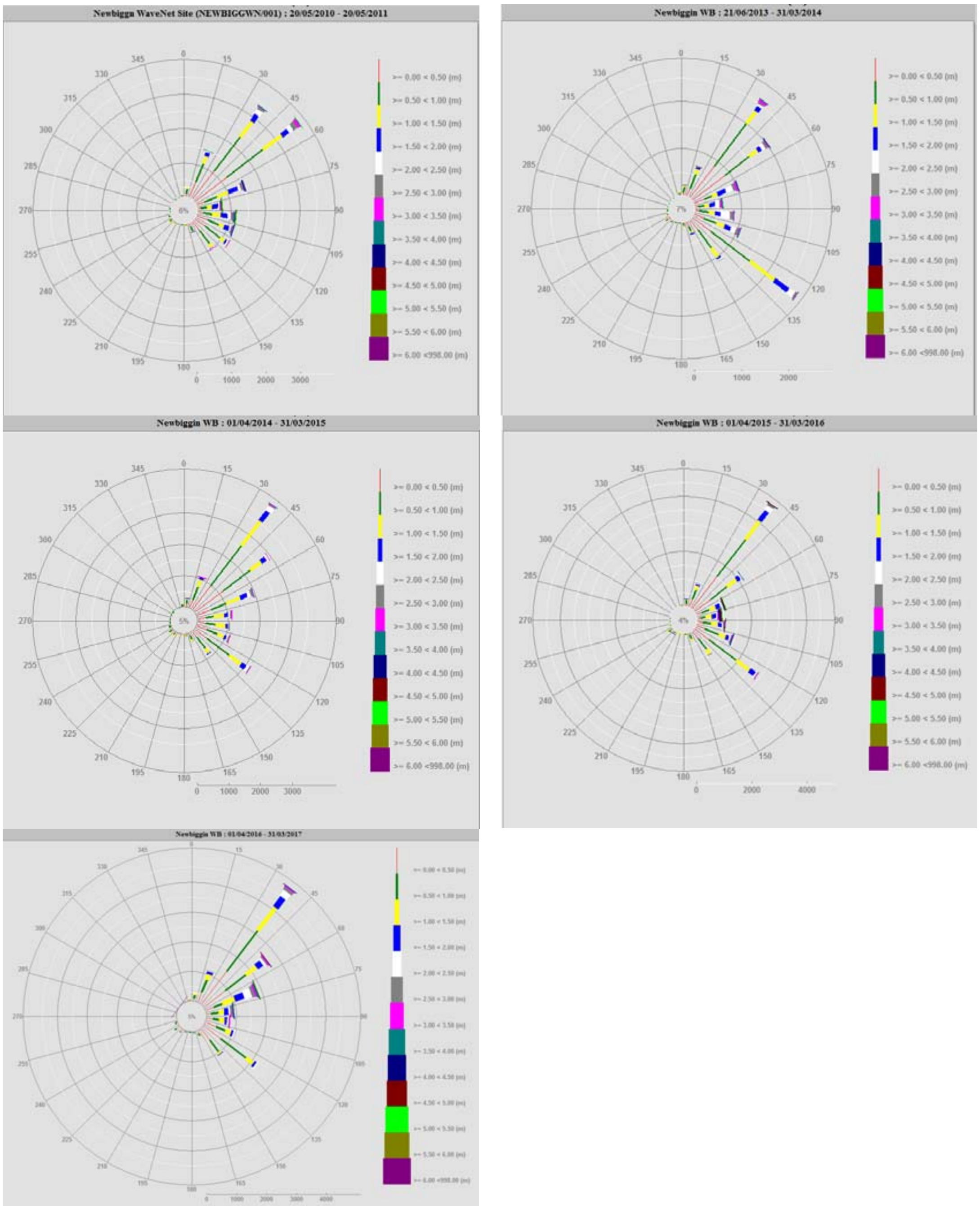


Figure 2.2 Wave roses for Newbiggin WB original deployment in 2010/11 and new data for 2013/14, 2014/15, 2015/16 and 2016/17

### 2.1.3. Storm Analysis

The baseline report storm analysis of the Newbiggin Ness wave dataset, undertaken using a wave height threshold of 3m and a storm separation threshold of 120 hours, is shown in Table 2-1. The 3m threshold was chosen in order to identify the largest 5 to 10 storms each year. This analysis used the full data range available, from 20/05/2010 to 07/06/2011. The storms recorded in the dataset arrive from the northeast to east directions (47 to 105 degrees). The storm with the largest wave height at peak in the baseline report data set, highlighted in bold, occurred on 8th to 10th November 2010.

***Table 2-1 Storm analysis for Newbiggin Ness (20/05/2010 to 07/06/2011)***

| **General Storm Information** | | | | | | | **At Peak** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Start Time** | **End Time** | **Dur (Hrs)** | **Peak of Storm**[1] | **Mean Dir (°)** | **No of Events** (30 min dataset) | **Mean Dir Vector (°)** | **Hs (m)** | **Tp (s)** | **Tz (s)** | **Dir (°)** | **Energy @ Peak (KJ/m/s)**[1] | **Total energy (KJ/m/s)** |
| 19/06/2010 07:00 | 20/06/2010 09:00 | 26.0 | 19/06/10 23:00 | 47 | 43 | 43 | 4.0 | 11.8 | 7.7 | 49 | 4.32 E+3 | 3.78 E+6 |
| 06/09/2010 18:30 | 07/09/2010 20:30 | 26.0 | 07/09/10 15:30 | 99 | 53 | 352 | 4.0 | 11.1 | 7.5 | 89 | 3.86 E+3 | 4.05 E+6 |
| 17/09/2010 10:00 | 17/09/2010 15:30 | 5.5 | 17/09/10 14:30 | 44 | 7 | 46 | 3.1 | 13.3 | 7.7 | 53 | 3.37 E+3 | 5.42 E+5 |
| 24/09/2010 03:00 | 25/09/2010 23:30 | 44.5 | 25/09/10 10:00 | 46 | 82 | 45 | 3.6 | 11.8 | 7.7 | 51 | 3.54 E+3 | 6.29 E+6 |
| 08/11/2010 12:30 | 10/11/2010 00:30 | 36.0 | 08/11/10 22:00 | 84 | 72 | 6 | 5.4 | 28.6 | 8.5 | 56 | 4.66 E+4 | 9.23 E+6 |
| 28/11/2010 10:30 | 02/12/2010 14:00 | 99.5 | 29/11/10 20:00 | 78 | 105 | 13 | 4.3 | 11.8 | 6.9 | 65 | 5.05 E+3 | 8.24 E+6 |
| 12/02/2011 01:30 | 12/02/2011 12:00 | 10.5 | 12/02/11 12:00 | 98 | 4 | 360 | 3.2 | 9.1 | 7.1 | 77 | 1.67 E+3 | 1.51 E+5 |
| 19/02/2011 06:00 | 19/02/2011 09:30 | 3.5 | 19/02/11 09:30 | 108 | 3 | 353 | 3.2 | 8.3 | 5.8 | 91 | 1.36 E+3 | 9.90 E+4 |

Notes: [1] The time of the storm peak is based on peak wave energy, which is calculated in SANDS using $E = \rho.g.H_s^2.L_o/8$, with the offshore wave length $L_o = g.Tp^2/2.\pi$

The results from storms analysis of the full set of new data is shown in Table 2-2 below. To aid interpretation of the results, alternate years have been shaded **and the storm with the largest peak wave height each year has been highlighted in bold**. The annual storm with the highest wave energy at peak has also been **highlighted in bold red text** as this depends on wave period as well as wave height and so is not always the same as the largest wave height. The longest storm in 2013 ran from 10th to 14th October and had peak wave height of 4.2m. There was one storm from the southeast in the record, occurring on 1st January 2014. It is notable that the storm that occurred on 5th / 6th December 2013, causing widespread damage to beaches and coastal defences on the east coast, had a peak wave height of 3.2m on the afternoon of 6th December at Newbiggin and while it had highest wave energy at peak and an unusually long wave period, it did not have the largest peak wave height.

There were six storms above the 3m threshold used at Newbiggin in 2015, which is similar to other years. The storm that started on 30th December had the highest significant wave height of 5.5m, with the peak on the 3rd January 2016. This storm also had the highest peak and total wave energy recorded at Newbiggin. In 2016 there were only four storms above the 3m threshold, which is relatively low compared to other years. The highest significant wave height of 5.3m occurred on 22nd November 2016. The highest peak and total energy were recorded 6th November 2016. In 2017 there have already been four storms recorded above the 3m threshold in just the first quarter of the year. The highest significant wave height of 4.3m was recorded on the 13th January 2017, this storm also had the highest peak energy recorded. Note that the analysis for the other Cell 1 wave buoys use higher thresholds of 4m due to their more exposed locations.

*Table 2-2 Storm analysis for Newbiggin WB (data 21/06/2013 to 31/03/2016)*

| General Storm Information | | | | | | | At Peak | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Start Time** | **End Time** | **Dur (hr)** | **Peak of Storm[1]** | **Mean Dir (°)** | **No Events** | **Mean Dir Vector (°)** | **Hs (m)** | **Tp (s)** | **Tz (s)** | **Dir (°)** | **Energy @ Peak KJ/m/s** | **Total Energy (KJ/m)** |
| 06/09/2013 18:30:00 | 06/09/2013 22:30:00 | 4.0 | 06/09/2013 22:30:00 | 47 | 8 | 44.9 | 3.1 | 9.1 | 5.9 | 48 | 1.5 E+3 | 3.2 E+5 |
| **10/10/2013 00:30:00** | **14/10/2013 08:00:00** | **103.5** | **10/10/2013 18:30:00** | **47** | **65** | **43.7** | **4.2** | **11.8** | **7.0** | **46** | **4.7 E+3** | **5.0 E+6** |
| 30/11/2013 01:00:00 | 30/11/2013 05:00:00 | 4.0 | 30/11/2013 05:00:00 | 38 | 5 | 54.9 | 3.1 | 11.1 | 7.4 | 37 | 2.4 E+3 | 3.1 E+5 |
| 06/12/2013 01:30:00 | 06/12/2013 21:30:00 | 20.0 | 06/12/2013 16:30:00 | 47 | 27 | 44.4 | 3.2 | 16.7 | 8.5 | 53 | **5.7 E+3** | 2.5 E+6 |
| 01/01/2014 16:30:00 | 01/01/2014 17:30:00 | 1.0 | 01/01/2014 17:30:00 | 142 | 2 | 329.2 | 3.1 | 8.3 | 5.8 | 118 | 1.3 E+3 | 6.1 E+4 |
| **19/01/2014 05:30:00** | **20/01/2014 10:30:00** | **29.0** | **19/01/2014 20:00:00** | **69** | **48** | **21.3** | **4.2** | **11.8** | **8.7** | **70** | **4.9 E+3** | **3.9 E+6** |
| 29/01/2014 04:00:00 | 05/02/2014 21:30:00 | 185.5 | 05/02/2014 18:30:00 | 100 | 63 | 350.2 | 3.8 | 10.0 | 6.7 | 114 | 2.8 E+3 | 3.7 E+6 |
| 12/02/2014 16:00:00 | 14/02/2014 19:30:00 | 51.5 | 12/02/2014 18:00:00 | 126 | 7 | 329.3 | 3.4 | 9.1 | 5.9 | 118 | 1.9 E+3 | 2.6 E+5 |
| 26/03/2014 23:00:00 | 28/03/2014 01:00:00 | 26.0 | 27/03/2014 00:00:00 | 73 | 12 | 20.1 | 3.4 | 11.1 | 6.7 | 68 | 2.9 E+3 | 7.6 E+5 |
| 07/10/2014 17:00:00 | 07/10/2014 21:00:00 | 4.0 | 07/10/2014 18:00:00 | 67 | 6 | 23.6 | 3.2 | 13.3 | 9.8 | 66 | 3.5 E+3 | 5.4 E+5 |
| 13/10/2014 21:30:00 | 14/10/2014 03:00:00 | 5.5 | 14/10/2014 00:00:00 | 78 | 9 | 16.5 | 3.3 | 8.3 | 6.1 | 76 | 1.4 E+3 | 3.2 E+5 |
| 13/11/2014 19:00:00 | 17/11/2014 13:30:00 | 90.5 | 17/11/2014 08:00:00 | 70 | 28 | 20.8 | 3.6 | 11.1 | 6.8 | 65 | 3.2 E+3 | 1.8 E+6 |
| 31/01/2015 22:00:00 | 01/02/2015 11:30:00 | 13.5 | 01/02/2015 00:00:00 | 36 | 26 | 53.7 | 3.4 | 11.8 | 6.7 | 41 | 3.2 E+3 | 1.7 E+6 |
| 21/03/2015 14:30:00 | 21/03/2015 16:00:00 | 1.5 | 21/03/2015 16:00:00 | 45 | 3 | 47.5 | 3.2 | 11.1 | 7.1 | 44 | 2.4 E+3 | 1.8 E+5 |
| 03/05/2015 08:30 | 03/05/2015 16:00 | 7.5 | 03/05/15 14:30 | 111 | 13 | 342.9 | 3.2 | 9.1 | 6.6 | 107 | 1.7 E+3 | 4.9 E+5 |
| 07/10/2015 06:30 | 07/10/2015 10:00 | 3.5 | 07/10/15 06:30 | 66 | 3 | 25.4 | 3.1 | 10.5 | 8.0 | 63 | 2.0 E+3 | 1.6 E+5 |
| 21/11/2015 02:30 | 21/11/2015 11:00 | 8.5 | 21/11/15 06:00 | 39 | 18 | 51.3 | 4.6 | 11.1 | 7.1 | 38 | 5.1 E+3 | 1.8 E+6 |
| **30/12/2015 11:30** | **07/01/2016 16:30** | **197.0** | **03/01/16 10:30** | **83** | **255** | **8.9** | **5.5** | **11.8** | **8.0** | **82** | **8.2 E+3** | **2.8 E+7** |
| 16/01/2016 00:00 | 16/01/2016 04:00 | 4.0 | 16/01/16 00:00 | 51 | 3 | 44.5 | 3.1 | 12.5 | 7.4 | 45 | 2.9 E+3 | 2.2 E+5 |
| **14/10/2016 06:30** | **16/10/2016 05:30** | **47.0** | **15/10/16 22:30** | 66 | 30 | 25.55 | 3.3 | 11.8 | 8.0 | 66 | 3.0 E+3 | 2.0 E+6 |
| 05/11/2016 03:30 | 07/11/2016 06:00 | 50.5 | 06/11/16 18:30 | 62 | 56 | 28.43 | 4.1 | 13.3 | 7.5 | 72 | **5.9 E+3** | 5.4 E+6 |
| 21/11/2016 18:30 | 22/11/2016 11:30 | 17.0 | 22/11/16 00:00 | **62** | **30** | **28.44** | **5.3** | **10.0** | **7.4** | **68** | **5.5 E+3** | **2.4 E+6** |
| 02/01/2017 05:30 | 04/01/2017 21:30 | 64.0 | 04/01/17 15:00 | 43 | 26 | 47.69 | 3.7 | 11.8 | 7.5 | 44 | 3.7 E+3 | 2.1 E+6 |
| 13/01/2017 11:00 | 13/01/2017 21:00 | 10.0 | 13/01/17 17:30 | **46** | **21** | **44.71** | **4.3** | **15.4** | **9.3** | **55** | **8.7 E+3** | **2.7 E+6** |
| 07/02/2017 21:00 | 13/02/2017 05:30 | 128.5 | 12/02/17 16:30 | 74 | 95 | 17.56 | 4.2 | 10.0 | 6.9 | 84 | 3.5 E+3 | 6.4 E+6 |
| 23/02/2017 14:30 | 23/02/2017 17:00 | 2.5 | 23/02/17 14:30 | 43 | 6 | 44.69 | 3.2 | 13.3 | 5.8 | 56 | 3.5 E+3 | 4.1 E+5 |

Notes: [1] The time of the storm peak is based on peak wave energy, which is calculated in SANDS using $E = \rho.g.H_s^2.L_o/8$, with the offshore wave length $L_o = g.Tp^2/2.\pi$

## 2.2. North Shields Tide gauge

The tide gauge at North Shields is operated continuously by the National Tide and Sea Level Facility (NTSLF) on behalf of the Environment Agency as part of the main UK tide gauge network. Information on this tide gauge installation is available on the NTSLF website: http://www.ntslf.org/tgi/portinfo?port=North_Shields including the site history reproduced below. The Chart Datum at North Shields is 2.6m below Ordnance Datum (http://www.ntslf.org/tides/datum). Due to its location in the mouth of the estuary the recorded water levels can be influenced by high freshwater flows in the river Tyne.

**Site history:**

- 1946 – Earliest data available
- 1974 – A Munro gauge was installed over one of the stilling wells and an Ott digital gauge over the other
- 1984 – The Ott digital gauge was removed and a Wellhead unit was installed
- 1984 – The DATARING system was installed with potentiometers attached to the Munro gauge and the Wellhead unit
- 1993 – All equipment removed while a new tide gauge building was built
- 1993 – New building completed and all equipment reinstated
- 1998 – Wind speed and direction instruments installed
- 1998 – Both stilling wells blocked - the POL diving team cleared the blockage
- 2000 – POL data logger installed.

***Table 2-3 Predicted tide levels at North Shields***

| Tidal State | Level (m Chart Datum) | Level (m Ordnance Datum) |
|---|---|---|
| HAT | 5.73 | 3.13 |
| LAT | 0.00 | -2.60 |
| MHWS | 5.12 | 2.52 |
| MHWN | 4.08 | 1.48 |
| MLWN | 1.90 | -0.70 |
| MLWS | 0.73 | -1.87 |
| Highest predicted 2014 | 5.68 | 3.08 |
| Lowest predicted 2014 | 0.08 | -2.52 |
| Highest predicted 2015 | 5.73 | 3.13 |
| Lowest predicted 2015 | 0.06 | -2.54 |
| Highest predicted 2016 | 5.68 | 3.08 |
| Lowest predicted 2016 | 0.10 | -2.50 |
| Highest predicted 2017 | 5.52 | 2.92 |
| Lowest predicted 2017 | 0.25 | -2.35 |
| Highest predicted 2018 | 5.56 | 2.96 |
| Lowest predicted 2018 | 0.1 | -2.50 |

Note: Based on data from http://www.ntslf.org/tgi/portinfo?port=North Shields

As described in the 2013-14 report, data is available on the internet in real time (http://www.ntslf.org/data/realtime?port=North_Shields) and quality controlled data can be downloaded from the British Oceanographic Data Centre (BODC) website.

The BODC data for January 2016 to March 2017 was downloaded and imported into SANDS for analysis alongside the other monitoring data. The data were adjusted from Chart Datum to Ordnance Datum during import to SANDS. A detailed plot of the data for 2016/17 is shown in Figure 2.3, showing that there were some significant gaps in the data, e.g. from 04/01/16 to 6/01/16 and between 15/05/2016 to 25/05/2016.

Although there is occasional data available from 1946, there are many large gaps in the record up until 1964, but the overall record appears very consistent. The spike in the high water levels shown near the end of the plot is the storm surge level of 3.98 mOD at 16:15 on the 5th December 2013. This shows how exceptional the conditions were, with the previous maximum recorded water level of 3.56m occurring at 17:00 on 31st January 1953 (note that prior to 1990 only hourly data are available and so the actual maximum water level in the 1953 storm event may have been higher than the recorded 3.56 mOD). Table 2-4 lists the 15 maximum observed water levels at North Shields.

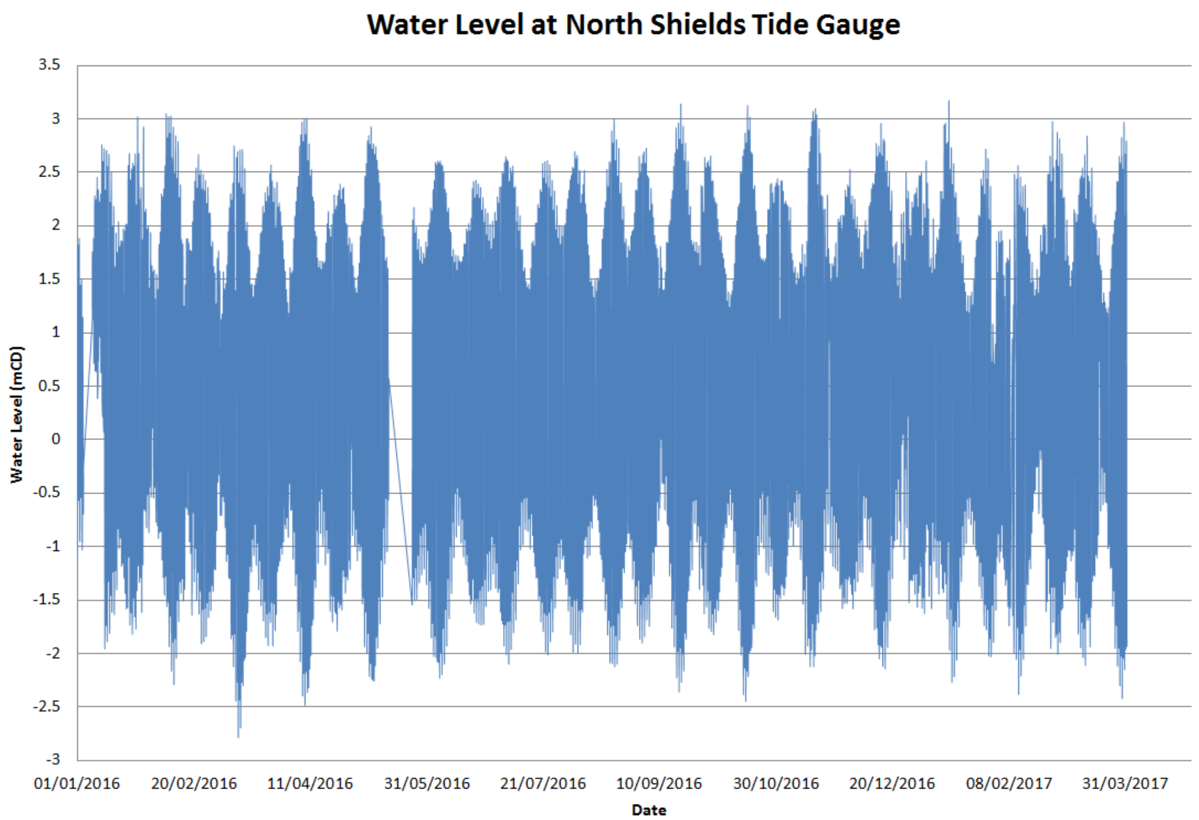



***Figure 2.3 Plot of water level data availability for 2016/17 at North Shields NTSLF Tide Gauge***

Note: For earlier years please refer to previous reports.

***Table 2-4 Maximum observed water levels at North Shields***

| Date | Level (mOD) |
|---|---|
| 05/12/2013 16:15 | 3.98 |
| 31/01/1953 17:00 | 3.56 |
| 12/01/2005 16:45 | 3.51 |
| 29/09/1969 05:00 | 3.50 |
| 27/11/2011 16:30 | 3.45 |
| 09/02/1997 16:30 | 3.38 |
| 27/02/1990 17:00 | 3.37 |
| 01/02/1983 18:00 | 3.37 |
| 04/01/2014 17:15 | 3.32 |
| 01/02/1995 16:00 | 3.31 |
| 26/02/1990 16:00 | 3.30 |
| 11/01/1993 05:00 | 3.28 |
| 25/10/1980 04:00 | 3.27 |
| 12/01/2009 16:15 | 3.27 |
| 25/11/2007 03:00 | 3.26 |

Based on analysis of data sourced from https://www.bodc.ac.uk/data/online_delivery/

## 2.3. Tyne Tees WaveNet Buoy

The full data set was re-downloaded from the Cefas website in order to obtain as much post-recovery data as available. However, the data from November 2016 to March 2017 is the telemetry data as the checked post-recovery data was not yet available for this period at the time of writing. There were also two significant gaps in the post-processed data (21/01/2008 to 08/04/2009 and 19/02/2014 to 12/05/2014) that were filled by telemetry data. There are no significant gaps in the 2016 data set before November 2016.

This buoy was deployed by Cefas in 2006 and continues to operate as part of the National Network managed by Cefas for the Environment Agency alongside the UK strategic tide gauge network. The wave buoy is located 35km offshore in around 65m water depth and therefore potentially provides a suitable baseline of offshore data as the record extends from before the Cell 1 strategic programme commenced in 2008.

The 2013-14 report included a comparison of the recorded waves at Newbiggin and Whitby under the Cell 1 programme to the WaveNet buoy Tyne Tees buoy and also modelled data from the Met Office hindcast model. This found that there are generally similarities between the data sets but also some significant differences, which mainly relate to differences in fetch lengths and sheltering by the coast at the different locations.

It was noted in the 2013-14 report that the hindcast wave data for the nearest Met Office hindcast location (2084) to the Tyne Tees buoy, which at the time of the analysis was available from 1980 to 2012, showed a very similar temporal variation to the measured data at Tyne Tees, but the highest significant wave height wave height on most storms was significantly under-estimated, with peak wave heights often greater than 0.5m below the measured value. This indicated that model calibration was poor for resolving peak wave heights during storms in this location. It was therefore recommended that caution should be used when using these data and that consideration be given to adjusting or calibrating the Met Office hindcast offshore data if it is to be used to define boundary conditions for coastal modelling studies in Cell 1. No further modelled data has been obtained for this update report, but the plot in Figure 2.4 showing a comparison of predicted and measured storms in November and December 2009 has been included from the previous report to demonstrate the issue.

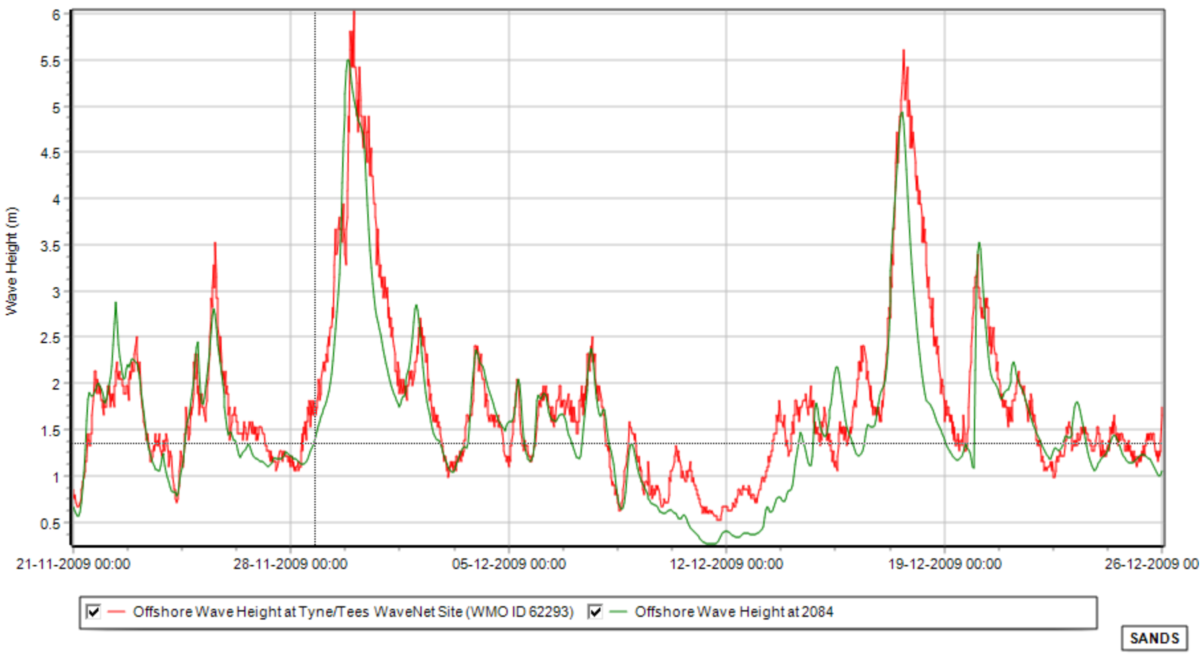



***Figure 2.4 Comparison of recorded and modelled wave heights at Tyne Tees in winter 2009 showing under-prediction of modelled data***

The data record that was reviewed at the Tyne Tees wave buoy for the baseline report ran from December 2006 to September 2012. This has been updated for this report with data to

March 2017. The scatter table and wave rose produced for the buoy now uses ten full years of wave data. Storm and extremes analyses have also been updated and are shown in the sub-sections below.

A comparison of wave heights at the Tyne/ Tees buoy to the data recorded at the Cell 1 programme buoys at Newbiggin, Whitby and Scarborough for 2016-17 is shown in Figure 2.5 below. This shows that generally the four wave buoys record similar storms. The highest storm wave heights are often observed at Tyne /Tees but this is not always the case; sometimes wave heights are larger at Scarborough. The largest storm in the period January 2016 to March 2017 was in January 2017. However, there were also significant storms in November.

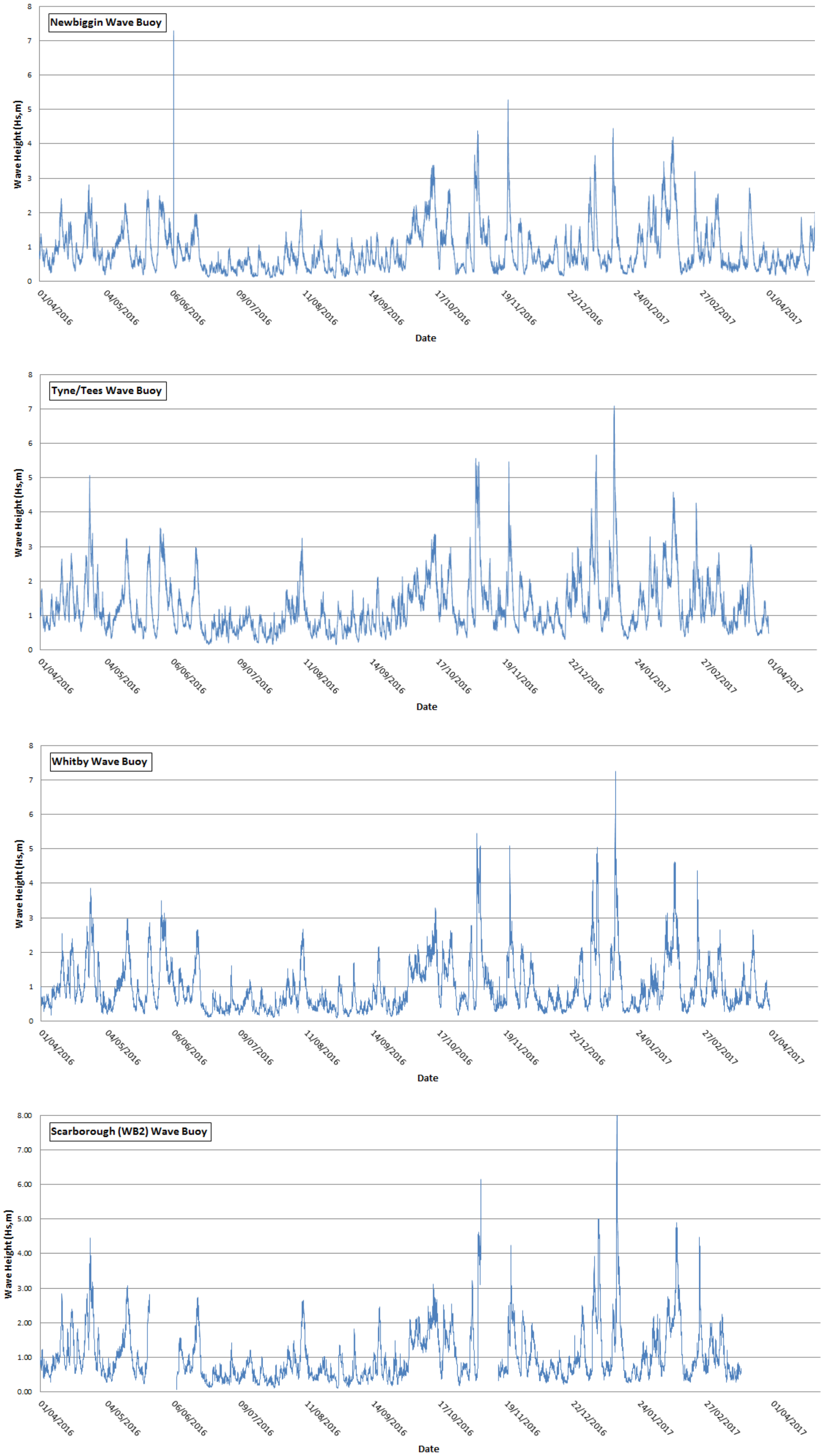



***Figure 2.5 Comparison of recorded wave heights at Tyne Tees to the Cell 1 programme buoys from April 2016 to March 2017***

### 2.3.1. Wave height vs Wave Period

The distribution of the wave height, peak and zero crossing period for the Tyne Tees wave data record is shown as a scatter plot in Figure 2.6. The plot shows some long period swell waves with heights of 0.5 to 1.5m and periods over 20s, and that the maximum storm wave heights of about 8m are associated with peak periods of 12 to 14s or zero crossing periods of 8 to 10s.

Note that the horizontal banding shown in the Tp values appears to be due to the post-processing undertaken by Cefas on the post recovery data as the plot in the previous report, which used the telemetry data, showed vertical rather than horizontal banding.

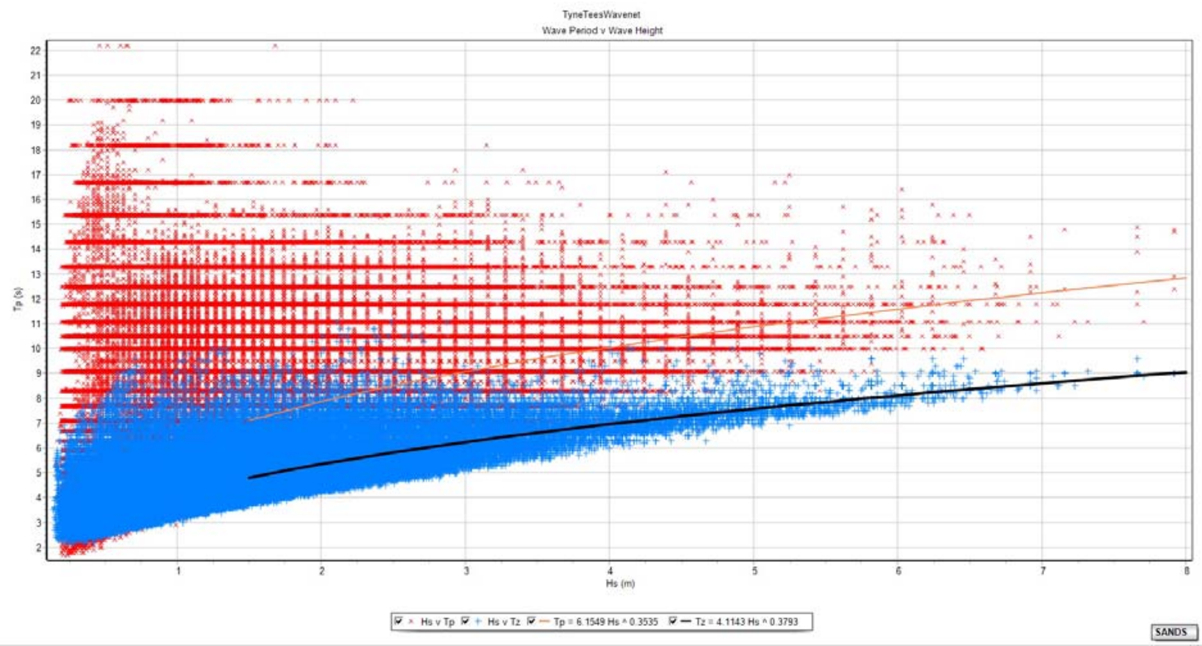



***Figure 2.6 Scatter plot of Wave Height Vs Peak Period at Tyne Tees wave buoy site***

### 2.3.2. Wave Rose and Wave Direction Scatter Tables

The wave rose for Tyne Tees in Figure 2.7 has been updated to include ten full years of wave data. The plot shows that the majority of the waves come from the north to north-northeast (0-30 degrees). There is a small secondary peak from the south east (120-150 degrees). Due to the offshore location of this buoy there are also small peaks from the southwest and northwest that would represent calm periods along most of the Cell 1 coast.

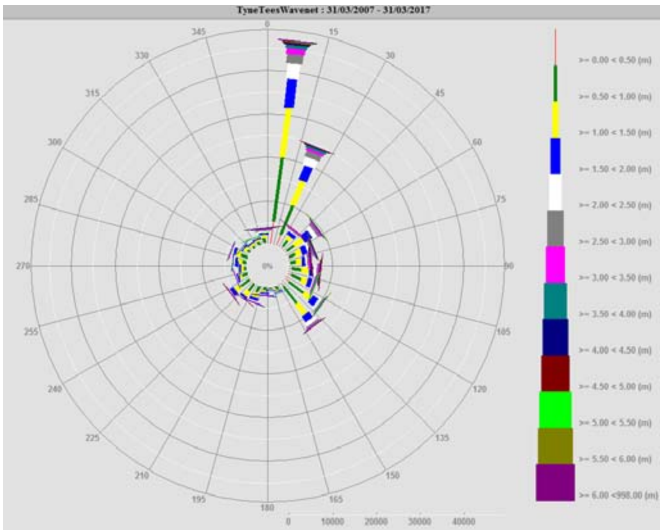



***Figure 2.7 Wave Rose at Tyne Tees wave buoy site (WMO ID 62293)***

### 2.3.3. Storm Analysis

A SANDS storm analysis of the Tyne Tees data set was undertaken using a wave height threshold of 4m and a storm separation threshold of 120 hours. This allows extraction of typically between three and ten of the biggest storms each year. The period of data examined ran from 07/12/2006 to 31/03/2017. As noted above, the analyses reported in previous reports have been updated by repeating the storms analysis with the quality controlled post-recovery data.

The storm analysis results are presented in Table 2-5 below. To aid interpretation of the results in Table 3.4, alternate years have been shaded **and the storm with the largest significant wave height each year has been highlighted in bold**. The annual storm with the highest wave energy at peak has also been **highlighted in bold red text** as this depends on wave period as well as wave height and so is not always the same as the largest wave height, e.g. in 2010 to 2015.

The storms mostly arrive from the north to northeast direction, 0 to 40 degrees, which has the longest fetch, but there are also a significant number of storms from other directions, particularly 80 to 140 degrees. The storm with largest Hs at peak (Hs = 7.9m) was associated with the second longest duration storm (180 hours) in March 2008.

Comparing the annual storm records, it can be seen that 2010 had the most storms (15). 2010 was also unusual in that the largest storm had an incident direction of 66 degrees at peak, whereas in most other years direction at peak of the largest storm was from the north to northeast sector (0 to 45 degrees). The longest duration storm (226hrs) was in 2012 and this also had an unusual direction at peak of 107 degrees. From these results we might expect that the alongshore drift on the Cell 1 beaches in 2010 and 2012 to have been atypical with unusual changes from the storm conditions. This was indeed noted in several of the 2010 Full Measures reports. For example the Hartlepool report noted unusual beach lowering along North Sands, and there was significant beach lowering at a number of locations at Sunderland.

The previously noted year with the fewest storms was 2011. This was reflected by accretion recorded in a number of the annual Full Measures reports. For example recovery of the beaches at North Sands and Middleton beaches in Hartlepool, and recovery of beaches was noted at Sunderland.

The winter of 2012 to 2013 suffered with larger storms than usual, with the second largest peak wave height recorded on 23rd March 2013. The longest duration storm in the record was from 5th to 15th December 2012. The storm surge that damaged many defences and received significant media attention on 5th and 6th December 2013 does not appear to have had exceptional wave conditions at the Tyne Tees buoy, with a peak significant wave height of 4.7m and storm duration of 38 hours. However, the wave period was over 14 seconds, which is unusual and the longest storm wave period recorded.

The latest data in Table 2-5 for this report shows there were only four storms in 2016, with one in January, one in April, and two in November . None of these storms appear particularly atypical from the overall record, although the storm in April was from the south-west. In 2017 to the end of April there were four storms already recorded above the threshold.

***Table 2-5 Storm Analysis at Tyne Tees WaveNet Buoy (data to 31st March 2017)***

| General Storm Information | | | | | | | At Peak | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| StartTime | EndTime | Dur (hr) | Peak of Storm[1] | Mean Dir (°) | No of Events | Mean Direction Vector (°) | Hs (m) | Tp (s) | Tz (s) | Dir (°) | Energy @ Peak (KJ/m/s) | Total Energy (KJ/m) |
| 19/03/2007 10:30 | 21/03/2007 05:30 | 43.0 | 20/03/07 14:30 | 21 | 73 | 79.0 | 6.2 | 14.8 | 8.5 | 23 | 1.68 E+4 | 1.59 E+7 |
| 25/06/2007 20:00 | 26/06/2007 13:30 | 17.5 | 26/06/07 10:00 | 33 | 28 | 81.5 | 4.4 | 10.3 | 7.2 | 23 | 4.03 E+3 | 2.73 E+6 |

| General Storm Information | | | | | | | At Peak | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| StartTime | EndTime | Dur (hr) | Peak of Storm[1] | Mean Dir (°) | No of Events | Mean Direction Vector (°) | Hs (m) | Tp (s) | Tz (s) | Dir (°) | Energy @ Peak (KJ/m/s) | Total Energy (KJ/m) |
| 26/09/2007 03:00 | 27/09/2007 05:00 | 26.0 | 26/09/07 19:00 | 10 | 36 | 80.3 | 4.6 | 13.8 | 7.6 | 6 | 7.77 E+3 | 4.05 E+6 |
| **08/11/2007 20:00** | **12/11/2007 15:00** | **91.0** | **09/11/07 08:30** | **14** | **64** | **78.7** | **6.2** | **15.9** | **9.0** | **6** | **1.94 E+4** | **1.86 E+7** |
| 19/11/2007 03:30 | 25/11/2007 21:30 | 162.0 | 23/11/07 05:00 | 74 | 59 | 78.7 | 4.9 | 12.7 | 7.6 | 17 | 7.61 E+3 | 8.15 E+6 |
| 08/12/2007 03:00 | 10/12/2007 14:30 | 59.5 | 08/12/07 03:30 | 65 | 11 | 85.0 | 4.1 | 12.8 | 7.6 | 17 | 5.40 E+3 | 1.23 E+6 |
| 03/01/2008 10:30 | 04/01/2008 01:30 | 15.0 | 03/01/08 23:30 | 77 | 24 | 14.6 | 4.2 | 10.9 | 7.6 | 62 | 4.21 E+3 | 2.51 E+6 |
| 01/02/2008 15:00 | 02/02/2008 09:30 | 18.5 | 02/02/08 00:00 | 37 | 34 | 80.8 | 6.0 | 16.4 | 9.0 | 17 | 1.93 E+4 | 9.60 E+6 |
| 10/03/2008 08:30 | 10/03/2008 12:30 | 4.0 | 10/03/08 11:00 | 146 | 9 | 307.5 | 4.6 | 9.6 | 6.5 | 141 | 3.76 E+3 | 7.34 E+5 |
| **17/03/2008 15:00** | **25/03/2008 03:00** | **180.0** | **22/03/08 05:00** | **59** | **78** | **83.8** | **7.9** | **14.8** | **9.0** | **6** | **2.71 E+4** | **2.30 E+7** |
| 05/04/2008 22:00 | 07/04/2008 05:00 | 31.0 | 06/04/08 19:00 | 45 | 22 | 83.7 | 4.6 | 13.9 | 7.6 | 6 | 7.89 E+3 | 3.27 E+6 |
| 20/07/2008 16:00 | 21/07/2008 09:30 | 17.5 | 20/07/08 23:30 | 15 | 8 | 76.0 | 4.2 | 11.8 | 7.6 | 11 | 4.94 E+3 | 9.08 E+5 |
| 03/10/2008 03:00 | 03/10/2008 20:30 | 17.5 | 03/10/08 16:30 | 30 | 32 | 82.4 | 4.7 | 13.6 | 7.6 | 23 | 8.13 E+3 | 5.18 E+6 |
| 21/11/2008 04:00 | 25/11/2008 12:30 | 104.5 | 22/11/08 11:30 | 15 | 112 | 75.8 | 6.0 | 15.6 | 8.5 | 11 | 1.74 E+4 | 2.22 E+7 |
| 10/12/2008 12:00 | 13/12/2008 18:00 | 78.0 | 13/12/08 08:00 | 109 | 37 | 332.1 | 4.9 | 10.0 | 7.2 | 129 | 4.72 E+3 | 4.01 E+6 |
| 31/01/2009 16:30 | 03/02/2009 09:00 | 64.5 | 02/02/09 22:00 | 84 | 57 | 7.2 | 5.8 | 11.4 | 8.5 | 84 | 8.68 E+3 | 8.10 E+6 |
| 23/03/2009 20:30 | 28/03/2009 20:30 | 120.0 | 28/03/09 18:30 | 92 | 26 | 89.6 | 4.9 | 11.0 | 7.6 | 0 | 5.71 E+3 | 3.16 E+6 |
| 10/07/2009 01:30 | 10/07/2009 02:30 | 1.0 | 10/07/09 01:30 | 13 | 2 | 79.0 | 4.2 | 11.9 | 7.2 | 11 | 5.02 E+3 | 2.28 E+5 |
| **29/11/2009 20:00** | **30/11/2009 15:00** | **19.0** | **30/11/09 00:30** | **17** | **39** | **73.3** | **6.0** | **11.2** | **8.0** | **11** | **8.99 E+3** | **6.26 E+6** |
| 17/12/2009 10:30 | 18/12/2009 05:00 | 18.5 | 17/12/09 19:30 | 64 | 36 | 26.2 | 5.4 | 12.7 | 8.0 | 68 | 9.38 E+3 | 5.72 E+6 |
| 30/12/2009 09:00 | 30/12/2009 23:00 | 14.0 | 30/12/09 12:30 | 84 | 25 | 7.9 | 5.1 | 9.0 | 7.2 | 90 | 4.09 E+3 | 2.29 E+6 |
| 06/01/2010 05:30 | 06/01/2010 11:00 | 5.5 | 06/01/10 06:30 | 30 | 10 | 63.7 | 4.2 | 12.7 | 7.2 | 11 | 5.72 E+3 | 1.10 E+6 |
| 29/01/2010 10:30 | 30/01/2010 00:30 | 14.0 | 29/01/10 22:30 | 6 | 29 | 83.7 | 5.4 | 10.2 | 8.0 | 6 | 6.05 E+3 | 3.01 E+6 |
| 26/02/2010 22:30 | 27/02/2010 02:30 | 4.0 | 27/02/10 01:00 | 18 | 7 | 72.4 | 4.6 | 10.1 | 7.6 | 17 | 4.16 E+3 | 7.04 E+5 |
| **19/06/2010 07:00** | **20/06/2010 08:30** | **25.5** | **19/06/10 20:00** | **21** | **49** | **69.2** | **5.4** | **12.7** | **7.6** | **23** | **9.38 E+3** | **8.47 E+6** |
| 29/08/2010 14:00 | 30/08/2010 06:30 | 16.5 | 29/08/10 22:30 | 145 | 27 | 91.8 | 4.9 | 10.6 | 7.6 | 0 | 5.30 E+3 | 2.91 E+6 |

| General Storm Information | | | | | | | At Peak | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| StartTime | EndTime | Dur (hr) | Peak of Storm[1] | Mean Dir (°) | No of Events | Mean Direction Vector (°) | Hs (m) | Tp (s) | Tz (s) | Dir (°) | Energy @ Peak (KJ/m/s) | Total Energy (KJ/m) |
| 06/09/2010 22:30 | 07/09/2010 16:00 | 17.5 | 07/09/10 15:30 | 101 | 23 | 353.1 | 4.6 | 10.5 | 8.0 | 90 | 4.50 E+3 | 2.32 E+6 |
| 17/09/2010 07:00 | 17/09/2010 18:30 | 11.5 | 17/09/10 08:30 | 10 | 17 | 80.7 | 4.7 | 13.1 | 8.0 | 11 | 7.54 E+3 | 2.85 E+6 |
| 24/09/2010 03:00 | 26/09/2010 00:00 | 45.0 | 24/09/10 10:00 | 19 | 89 | 72.9 | 5.3 | 12.1 | 8.0 | 11 | 7.96 E+3 | 1.32 E+7 |
| 19/10/2010 23:30 | 24/10/2010 16:30 | 113.0 | 20/10/10 10:00 | 13 | 17 | 78.2 | 4.2 | 13.4 | 7.2 | 17 | 6.37 E+3 | 1.90 E+6 |
| 08/11/2010 14:00 | 09/11/2010 20:30 | 30.5 | 09/11/10 10:00 | 87 | 60 | 3.4 | 5.6 | 10.5 | 8.0 | 73 | 6.87 E+3 | 7.81 E+6 |
| 17/11/2010 11:00 | 17/11/2010 18:30 | 7.5 | 17/11/10 12:00 | 135 | 10 | 322.2 | 4.7 | 9.2 | 6.9 | 129 | 3.72 E+3 | 8.09 E+5 |
| 29/11/2010 19:30 | 02/12/2010 08:30 | 61.0 | 29/11/10 21:00 | 80 | 46 | 11.7 | 5.1 | 11.2 | 7.6 | 56 | 6.33 E+3 | 5.52 E+6 |
| 16/12/2010 15:00 | 17/12/2010 06:30 | 15.5 | 17/12/10 03:30 | 10 | 27 | 80.5 | 4.6 | 12.5 | 7.6 | 17 | 6.38 E+3 | 3.18 E+6 |
| **23/07/2011 14:00** | **24/07/2011 11:00** | **21.0** | **24/07/11 03:00** | **23** | **39** | **67.1** | **4.7** | **12.8** | **7.6** | **17** | **7.20 E+3** | **5.76 E+6** |
| 24/10/2011 18:30 | 25/10/2011 09:30 | 15.0 | 25/10/11 09:30 | 103 | 26 | 348.5 | 4.1 | 11.3 | 6.9 | 79 | 4.21 E+3 | 2.57 E+6 |
| 09/12/2011 08:30 | 09/12/2011 12:00 | 3.5 | 09/12/11 10:30 | 6 | 6 | 83.8 | 4.5 | 14.3 | 8.3 | 6 | **8.02 E+3** | 1.16 E+6 |
| 05/01/2012 15:30 | 06/01/2012 05:00 | 13.5 | 06/01/12 03:00 | 11 | 23 | 79.5 | 4.6 | 12.5 | 7.6 | 17 | 6.38 E+3 | 2.88 E+6 |
| 03/04/2012 13:30 | 04/04/2012 10:30 | 21.0 | 03/04/12 16:00 | 64 | 43 | 26.5 | 5.3 | 10.5 | 7.3 | 49 | 6.04 E+3 | 5.51 E+6 |
| 24/09/2012 08:30 | 25/09/2012 10:30 | 26.0 | 25/09/12 01:30 | 74 | 50 | 16.7 | 4.7 | 12.3 | 8.0 | 62 | 6.65 E+3 | 7.38 E+6 |
| 26/10/2012 16:30 | 27/10/2012 14:30 | 22.0 | 26/10/12 23:00 | 10 | 37 | 80.5 | 4.9 | 15.3 | 7.6 | 11 | 1.10 E+4 | 5.74 E+6 |
| 05/12/2012 16:00 | 15/12/2012 01:30 | 225.5 | 14/12/12 19:30 | 53 | 47 | 38.4 | 5.4 | 10.5 | 7.6 | 96 | 6.41 E+3 | 5.62 E+6 |
| **20/12/2012 06:00** | **21/12/2012 14:30** | **32.5** | **20/12/12 23:00** | **103** | **62** | **347.6** | **5.6** | **11.3** | **8.0** | **96** | **7.95 E+3** | **8.62 E+6** |
| 18/01/2013 18:30 | 22/01/2013 06:00 | 83.5 | 21/01/13 10:00 | 81 | 56 | 8.9 | 6.7 | 11.2 | 8.5 | 84 | 1.10 E+4 | 1.11 E+7 |
| 06/02/2013 08:00 | 07/02/2013 06:00 | 22.0 | 06/02/13 12:30 | 42 | 45 | 82.2 | 5.4 | 11.9 | 7.6 | 11 | 8.23 E+3 | 6.71 E+6 |
| 07/03/2013 21:00 | 10/03/2013 21:30 | 72.5 | 08/03/13 04:00 | 65 | 40 | 25.5 | 4.9 | 10.7 | 7.6 | 73 | 5.40 E+3 | 4.36 E+6 |
| 18/03/2013 09:00 | 25/03/2013 01:30 | 160.5 | 23/03/13 14:30 | 85 | 157 | 5.0 | 6.0 | 12.1 | 8.0 | 90 | 1.05 E+4 | 2.81 E+7 |
| **23/05/2013 18:00** | **24/05/2013 12:00** | **18.0** | **23/05/13 22:30** | **13** | **35** | **77.3** | **6.7** | **12.5** | **8.5** | **17** | **1.37 E+4** | **7.14 E+6** |
| 10/09/2013 13:00 | 10/09/2013 19:30 | 6.5 | 10/09/13 14:00 | 11 | 14 | 79.4 | 4.4 | 11.0 | 7.2 | 11 | 4.60 E+3 | 1.51 E+6 |
| 09/10/2013 21:30 | 11/10/2013 09:00 | 35.5 | 10/10/13 21:30 | 65 | 65 | 79.5 | 5.6 | 12.5 | 7.8 | 25 | **9.53 E+3** | 1.25 E+7 |

| General Storm Information | | | | | | | At Peak | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| StartTime | EndTime | Dur (hr) | Peak of Storm[1] | Mean Dir (°) | No of Events | Mean Direction Vector (°) | Hs (m) | Tp (s) | Tz (s) | Dir (°) | Energy @ Peak (KJ/m/s) | Total Energy (KJ/m) |
| 29/11/2013 22:30 | 30/11/2013 06:30 | 8.0 | 30/11/13 00:30 | 42 | 17 | 84.5 | 5.6 | 12.7 | 8.0 | 11 | 1.00 E+4 | 3.28 E+6 |
| 05/12/2013 14:00 | 07/12/2013 04:30 | 38.5 | 06/12/13 20:00 | 24 | 60 | 80.8 | 4.7 | 17.0 | 9.0 | 6 | 1.27 E+4 | 1.17 E+7 |
| 27/12/2013 09:30 | 27/12/2013 12:30 | 3.0 | 27/12/13 10:00 | 218 | 3 | 248.9 | 4.1 | 7.3 | 6.5 | 203 | 1.76 E+3 | 1.34 E+5 |
| 05/02/2014 04:00 | 05/02/2014 18:00 | 14.0 | 05/02/14 05:30 | 139 | 9 | 318.6 | 4.4 | 9.3 | 6.9 | 129 | 3.29 E+3 | 7.19 E+5 |
| **12/02/2014 20:00** | **14/02/2014 19:30** | **47.5** | **12/02/14 21:00** | **172** | **12** | **279.1** | **4.6** | **8.9** | **6.5** | **141** | **3.23 E+3** | **8.58 E+5** |
| 21/10/2014 22:00 | 22/10/2014 01:30 | 3.5 | 21/10/14 23:00 | 6 | 5 | 84.0 | 4.4 | 11.5 | 7.6 | 6 | 5.03 E+3 | 6.03 E+5 |
| 31/01/2015 09:30 | 01/02/2015 19:30 | 34.0 | 31/01/15 23:30 | 66 | 66 | 87.9 | 6.2 | 13.1 | 8.0 | 6 | 1.32 E+4 | 1.29 E+7 |
| 03/09/2015 05:30 | 04/09/2015 06:00 | 24.5 | 03/09/15 18:30 | 13 | 15 | 78.1 | 4.4 | 10.5 | 6.8 | 11 | 4.25 E+3 | 1.56 E+6 |
| **21/11/2015 01:30** | **21/11/2015 14:30** | **13.0** | **21/11/15 05:30** | **72** | **27** | **85.9** | **7.1** | **11.8** | **8.5** | **356** | **1.38 E+4** | **5.70 E+6** |
| 30/12/2015 09:30 | 07/01/2016 12:00 | 194.5 | 03/01/16 13:00 | 81 | 190 | 10.3 | 5.3 | 11.8 | 8.5 | 75 | 7.63 E+3 | 2.48 E+7 |
| 14/01/2016 11:00 | 16/01/2016 03:00 | 40.0 | 15/01/16 23:30 | 58 | 19 | 80.8 | 4.7 | 12.5 | 7.8 | 27 | 6.92 E+3 | 2.12 E+6 |
| 25/04/2016 19:30 | 26/04/2016 03:00 | 7.5 | 25/04/16 23:00 | 239 | 13 | 89.2 | 5.1 | 11.8 | 7.9 | 359 | 7.11 E+3 | 1.73 E+6 |
| 05/11/2016 04:00 | 07/11/2016 02:30 | 46.5 | 06/11/16 20:00 | 76 | 82 | 65.2 | 5.4 | 12.5 | 8.0 | 63 | 8.89 E+3 | 1.28 E+7 |
| **21/11/2016 18:30** | **21/11/2016 23:30** | **5.0** | **21/11/16 20:30** | **63** | **11** | **27.7** | **5.5** | **9.5** | **7.3** | **58** | **5.31 E+3** | **1.18 E+6** |
| 02/01/2017 05:00 | 04/01/2017 22:00 | 65.0 | 04/01/17 14:00 | 13 | 35 | 77.9 | 5.0 | 14.3 | 8.3 | 10 | 1.01 E+4 | 5.98 E+6 |
| 13/01/2017 08:00 | 14/01/2017 08:00 | 24.0 | 13/01/17 16:30 | 85 | 48 | 78.1 | 6.5 | 15.4 | 8.8 | 11 | 1.98 E+4 | 1.30 E+7 |
| 12/02/2017 02:30 | 12/02/2017 21:00 | 18.5 | 12/02/17 07:00 | 74 | 29 | 17.3 | 4.4 | 10.5 | 7.1 | 66 | 4.25 E+3 | 2.93 E+6 |
| 23/02/2017 15:00 | 23/02/2017 18:30 | 3.5 | 23/02/17 15:00 | 14 | 5 | 77.1 | 4.3 | 12.5 | 6.7 | 13 | 5.59 E+3 | 5.80 E+5 |

Notes: [1] The time of the storm peak is based on peak wave energy, which is calculated in SANDS using $E = \rho.g.H_s^2.L_o/8$, with the offshore wave length $L_o = g.Tp^2/2.\pi$

## 2.4. Whitby Waverider Buoy

In the baseline report, one full year's data for Whitby (October 2010 to October 2011) was analysed in SANDS to prepare a baseline wave rose and scatter table. The new data collected is from a very similar location and now covers the period from 17th January 2013 to 31st March 2017. The data were imported into SANDS for comparison and analysis alongside the other available monitoring data; see Figure 2.5.

Supporting monthly plots of the new data are provided in Appendix C.

### 2.4.1. Wave Height vs Peak Period

The distribution of the wave height and period for the wave data record has been plotted as a scatter plot with the data for 1st April to 31st March each year overlaid on the baseline data (20/05/2010 to 04/11/2011); see Figure 2.8 below. Different symbols have been used to distinguish the baseline data from 2010/11 and different years of the current deployment. The distribution of wave height and period appears similar between the years, although 2013/14 data includes a number of longer wave periods for wave heights in the 2m to 5m range. There are several larger storm waves in the new data set with Hs>6m, similar to the 2015/16 data set. The 0-2m wave height range also includes quite a lot of longer wave preiods than in previous years.

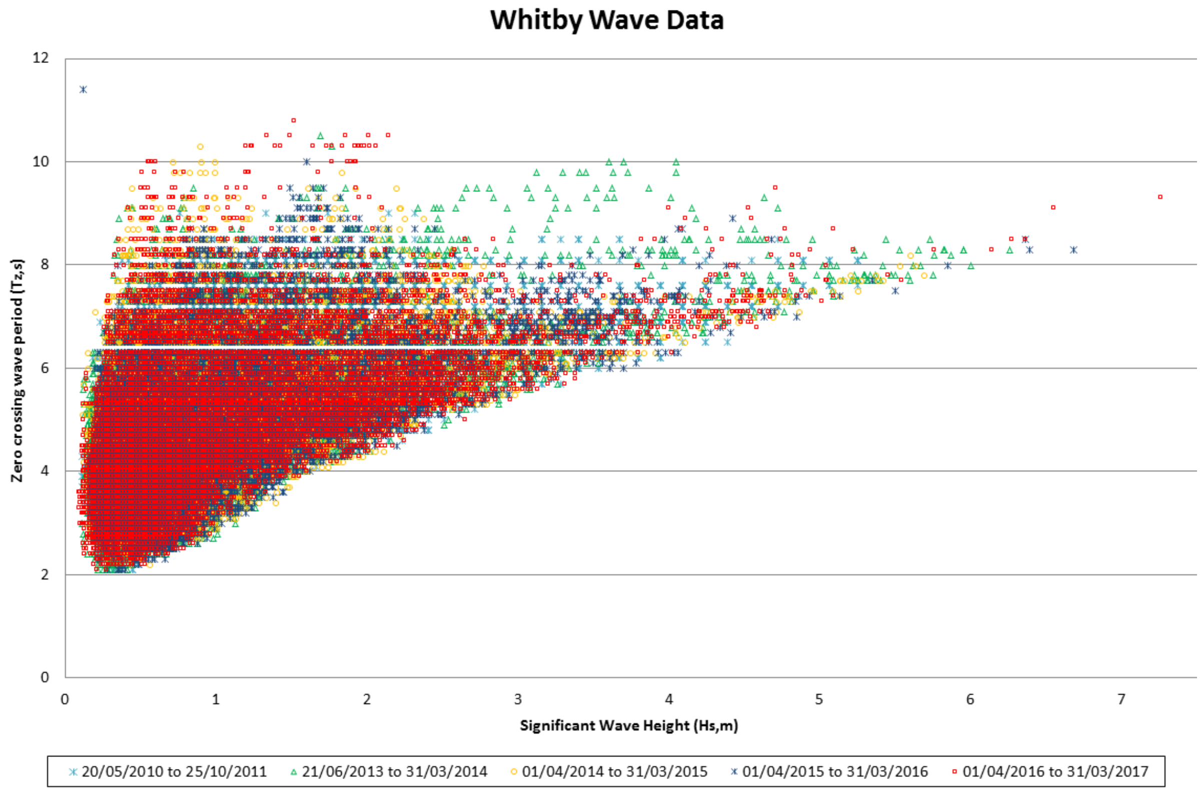



***Figure 2.8 Scatter plot of Wave Height Vs Zero crossing period at Whitby wave buoy site***

### 2.4.2. Wave Rose

The directional data of the wave record has also been used to plot wave roses for the baseline and new data sets, which all show a quite similar distribution, see Figure 2.9 below. The wave roses are fairly similar and show that the waves predominantly approach the coastline at Whitby from the northeast by north direction (0 to 30 degrees).

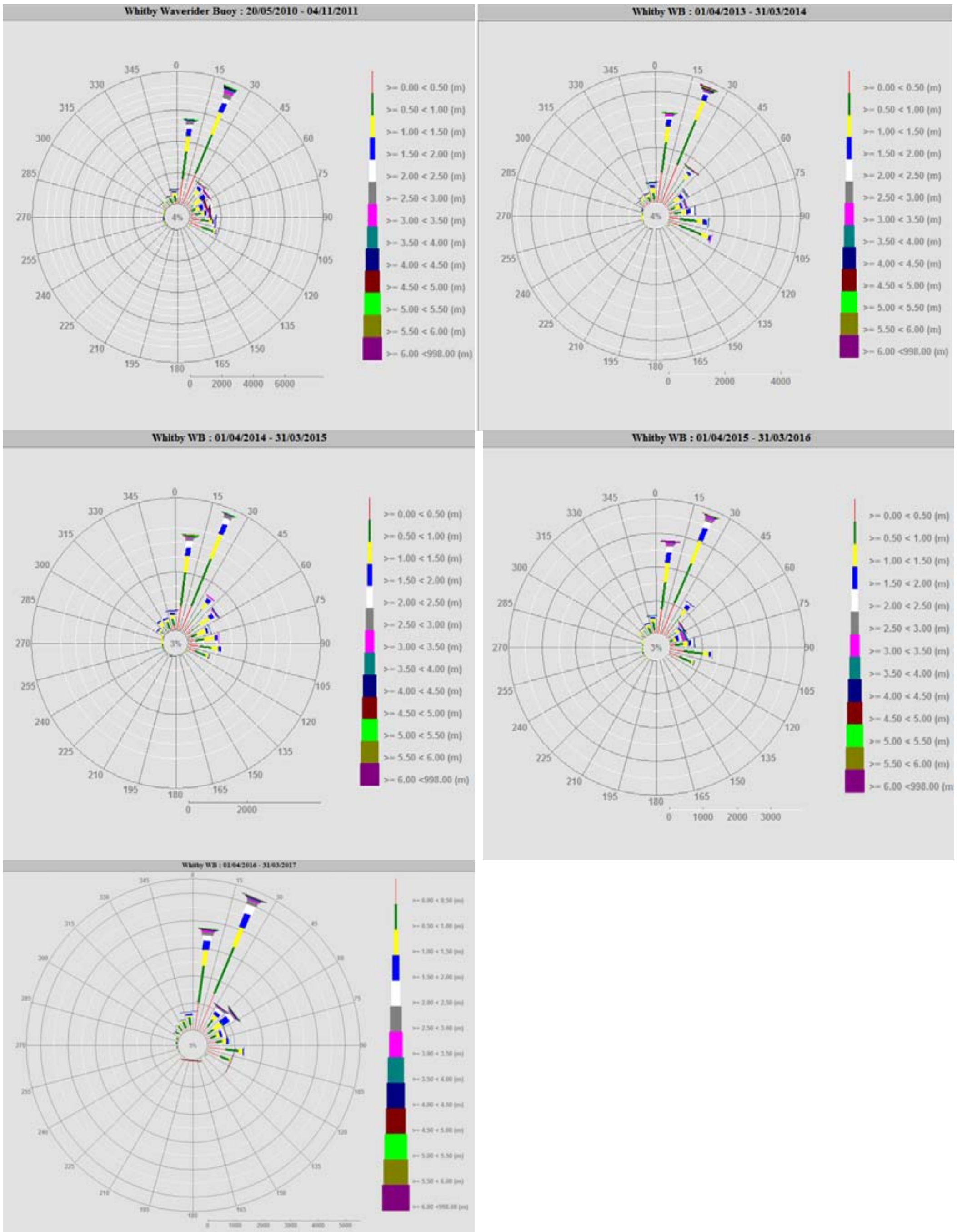



***Figure 2.9 Wave Roses at Whitby wave buoy site***

### 2.4.3. Storm Analysis

A storm analysis of the baseline Whitby data set was originally undertaken for the baseline report using a wave height threshold of 4m and a storm separation threshold of 120 hours. The period of data examined ran from 20/05/2010 to 25/10/2011. The analysis was revised for the 2014/15 report using a slightly lower threshold of 3.9m to detect more storms and the updated results with the latest data now to 31/03/2017 are presented in Table 2-6 below. The storms mostly arrive from the north to east-northeast (5 to 66 degrees). The storm in the baseline record with the previous largest wave height (5.1m $H_{mo}$) at peak occurred on 25$^{th}$ September 2010. The storms analysis of the new data is shown in Table 2-7. To aid interpretation of the results in the storm Tables alternate years have been shaded **and the storm with the largest peak wave height each year has been highlighted in bold**. The annual storm with the highest wave energy at peak has also been **highlighted in bold red text** as this depends on wave period as well as wave height and so is not always the same.

*Table 2-6 Storm Analysis results for Whitby – Baseline data 20/05/2010 to 25/10/2011*

| General Storm Information | | | | | At Peak | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Start Time | End Time | Duration (Hours) | Peak of Storm[1] | Mean Dir (°) | No of Events (30 min dataset) | Mean Dir Vector (°) | Hs (m) | Tp (s) | Dir (°) | Energy @ Peak (KJ/m/s) | Total Energy (KJ/m) |
| 19/06/2010 08:30 | 20/06/2010 09:30 | 25.0 | 20/06/10 00:00 | 26 | 47 | 64.7 | 4.9 | 13.5 | 28 | 8.6 E+3 | 7.6 E+6 |
| 29/08/2010 15:00 | 30/08/2010 06:30 | 15.5 | 29/08/10 17:30 | 6 | 16 | 84.4 | 4.4 | 9.5 | 6 | 3.5 E+3 | 1.4 E+6 |
| 17/09/2010 09:00 | 17/09/2010 12:30 | 3.5 | 17/09/10 11:00 | 24 | 3 | 67.5 | 4.4 | 13.5 | 22 | 6.9 E+3 | 5.8 E+5 |
| **24/09/2010 05:30** | **26/09/2010 04:00** | **46.5** | **25/09/10 17:00** | **24** | **84** | **66.6** | **5.1** | 12.2 | **28** | **7.5 E+3** | **1.2 E+7** |
| 20/10/2010 08:00 | 20/10/2010 11:30 | 3.5 | 20/10/10 11:30 | 26 | 3 | 69.0 | 3.9 | 11.0 | 22 | 4.9 E+3 | 3.2 E+5 |
| 08/11/2010 17:30 | 09/11/2010 19:00 | 25.5 | 09/11/10 05:30 | 66 | 28 | 25.4 | 4.7 | 11.8 | 68 | 5.3 E+3 | 3.1 E+6 |
| 29/11/2010 19:30 | 02/12/2010 01:30 | 54.0 | 29/11/10 22:00 | 61 | 24 | 29.9 | 4.7 | 12.8 | 56 | 6.1 E+3 | 2.8 E+6 |
| 16/12/2010 19:00 | 16/12/2010 20:30 | 1.5 | 16/12/10 20:30 | 14 | 2 | 78.5 | 3.9 | 9.1 | 17 | 3.6 E+3 | 1.7 E+5 |
| 23/07/2011 15:30 | 24/07/2011 11:00 | 19.5 | 24/07/11 03:00 | 28 | 36 | 62.1 | 4.2 | 10.8 | 22 | 5.8 E+3 | 4.9 E+6 |

Notes: [1] The time of the storm peak is based on peak wave energy, which is calculated in SANDS using $E = \rho.g.H_s^2.L_o/8$, with the offshore wave length $L_o = g.Tp^2/2.\pi$

Comparing the storm data at Whitby in Table 2-6 and Table 2-7 with those in Table 2-1 and Table 2-2 for Newbiggin, it can be seen that several of the storms were recorded at both locations, but the durations, peak wave heights and directions for the storms were quite different. Due to the differing conditions the storm analysis also identified different storms at both locations.

*Table 2-7 Storm analysis for Whitby WB (data 17/01/2013 to 31/03/2017)*

| General Storm Information | | | | | | | At Peak | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| StartTime | EndTime | Duration (hr) | Peak of Storm | Mean Dir (°) | No of Events | Mean Direction Vector | Hs (m) | Tp (s) | Tz (s) | Dir (°) | Energy @ Peak (KJ/m/s) | Total Energy (KJ/m) |
| 21/01/2013 02:30 | 22/01/2013 03:00 | 24.5 | 21/01/13 14:30 | 64 | 38 | 26.7 | 5.0 | 11.1 | 8.2 | 61 | 6.0 E+3 | 5.0 E+6 |
| 06/02/2013 11:00 | 07/02/2013 04:00 | 17.0 | 06/02/13 18:30 | 17 | 35 | 73.5 | 4.8 | 11.8 | 7.1 | 16 | 6.4 E+3 | 4.3 E+6 |
| 08/03/2013 03:30 | 11/03/2013 05:30 | 74.0 | 11/03/13 04:00 | 58 | 12 | 35.5 | 4.3 | 10.0 | 7.1 | 45 | 3.7 E+3 | 1.1 E+6 |
| 18/03/2013 18:30 | 24/03/2013 17:30 | 143.0 | 23/03/13 13:00 | 70 | 95 | 20.3 | 5.2 | 11.1 | 8.2 | 72 | 6.6 E+3 | 1.2 E+7 |
| **23/05/2013 21:00** | **24/05/2013 12:30** | **15.5** | **24/05/13 00:00** | **20** | **27** | **70.3** | **5.8** | 12.5 | **8.3** | **24** | **1.0 E+4** | **5.0 E+6** |
| 10/09/2013 14:00 | 10/09/2013 22:30 | 8.5 | 10/09/13 16:00 | 19 | 17 | 71.5 | 4.4 | 11.1 | 6.9 | 24 | 4.6 E+3 | 1.8 E+6 |
| 10/10/2013 01:30 | 11/10/2013 06:30 | 29.0 | 11/10/13 00:00 | 30 | 57 | 69.2 | 5.7 | 13.3 | 8.3 | 31 | 1.1 E+4 | 1.1 E+7 |
| 30/11/2013 00:00 | 30/11/2013 06:30 | 6.5 | 30/11/13 03:30 | 16 | 13 | 74.8 | 4.8 | 12.5 | 7.4 | 20 | 7.1 E+3 | 2.1 E+6 |
| 05/12/2013 20:00 | 06/12/2013 22:00 | 26.0 | 06/12/13 19:30 | 20 | 45 | 70.6 | 4.7 | 16.7 | 9.1 | 32 | 1.2 E+4 | 8.2 E+6 |
| **14/10/2014 04:30** | **14/10/2014 05:30** | **1.0** | **14/10/14 05:30** | **52** | **2** | **40.3** | **4.1** | 8.3 | **6.5** | **53** | **2.3 E+3** | **1.2 E+5** |
| 31/01/2015 10:30 | 01/02/2015 18:00 | 31.5 | 01/02/15 02:30 | 14 | 60 | 79.1 | **5.7** | 11.8 | 7.8 | 11 | 8.9 E+3 | 9.0 E+6 |
| 03/09/2015 18:30 | 04/09/2015 07:00 | 12.5 | 03/09/15 18:30 | 26 | 3 | 64.9 | 3.9 | 10.5 | 6.5 | 27 | 3.3 E+3 | 2.6 E+5 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **21/11/2015 07:00** | **21/11/2015 15:30** | **8.5** | **21/11/15 07:30** | **16** | **14** | **75.3** | **6.7*** | **12.5*** | **8.3*** | **14** | **1.4 E+4** | **2.7 E+6** |
| 03/01/2016 08:00 | 06/01/2016 13:00 | 77.0 | 03/01/16 10:00 | 63 | 20 | 29.3 | 4.7 | 11.1 | 8.5 | 58 | **5.3 E+3** | 2.2 E+6 |
| 14/01/2016 13:00 | 16/01/2016 06:00 | 41.0 | 14/01/16 13:30 | 10 | 12 | 80.3 | 4.7 | 10.5 | 7.1 | 0 | 4.8 E+3 | 1.3 E+6 |
| 05/11/2016 06:00 | 07/11/2016 02:00 | 44.0 | 05/11/16 06:00 | 50 | 62 | 58.8 | 4.8 | 28.6 | 8.0 | 191 | 3.8 E+4 | 9.7 E+6 |
| **21/11/2016 18:30** | **21/11/2016 22:30** | **4.0** | **21/11/16 21:00** | **50** | **9** | **40.8** | **5.1** | **9.1** | **7.4** | **52** | **4.2 E+3** | **8.3 E+5** |
| 02/01/2017 06:30 | 04/01/2017 21:30 | 63.0 | 04/01/17 12:30 | 21 | 32 | 70.5 | 4.9 | 12.5 | 8.3 | 23 | 7.5 E+3 | 5.0 E+6 |
| 13/01/2017 09:30 | 14/01/2017 03:00 | 17.5 | 13/01/17 19:00 | **27** | **24** | **70.5** | **6.6** | **14.3** | **9.1** | **24** | **1.7 E+4** | **5.5 E+6** |
| 12/02/2017 02:30 | 12/02/2017 19:30 | 17.0 | 12/02/17 05:00 | 55 | 26 | 35.8 | 4.6 | 10.5 | 7.3 | 48 | 4.7 E+3 | 2.7E+6 |
| 23/02/2017 18:00 | 23/02/2017 19:00 | 1.0 | 23/02/17 18:00 | 23 | 2 | 73.3 | 4.4 | 9.1 | 6.8 | 14 | 3.1 E+3 | 1.2 E+5 |

Note *= As noted in the CCO annual report in Appendix E, the waves were breaking at the buoy location during several hours of this storm.

The previous storms analyses at Whitby had showed that the largest recorded peak wave energy was associated with the storm that occurred from 5th to 6th December 2013, although it did not have the largest wave height. The largest peak wave height in the record was previously 6.7m during the short storm on 21st November 2015 which also had the highest wave energy at the peak of the storm. The storm recorded on the 13th January 2017 has surpassed the previously recorded peak wave energy.

As only five years' wave data are available, it is not yet possible to place these conditions in a longer-term context. Further insight into this can be gained by reference to the longer data set from the Tyne Tees wave buoy, or the longer term Met Office model data analysed in the 2013-14 report.

## 2.5. Whitby NTSLF Tide Gauge

There is a tide gauge at Whitby that is operated continuously by the National Tide and Sea Level Facility (NTSLF) on behalf of the Environment Agency as part of the main UK tide gauge network. Information on this tide gauge installation is available on the NTSLF website: http://www.ntslf.org/tgi/portinfo?port=Whitby, including the site history reproduced below. The Chart Datum at Whitby is 3m below Ordnance Datum (http://www.ntslf.org/tides/datum). Due to its location in the mouth of the estuary the recorded water levels can be significantly influenced by high freshwater flows in the River Esk.

**Whitby Tide Gauge Site history**

- 1980 – Installed Aanderaa recorder attached to a pneumatic bubbler
- 1989 – DATARING system installed with full-tide pressure points; the Aanderaa recorder was removed
- 1995 – New steel work with two full-tide and mid-tide measuring systems installed
- 2002 – POL data logger installed.

Note that the issues with missing extreme low water level measurements are noted on the PSMSL website, see further information in Section 3.4.

Data is available on the internet in real time (http://www.ntslf.org/data/realtime?port=Whitby ) and quality controlled data can be downloaded from the British Oceanographic Data Centre (BODC) website.

The data available for analysis at the time of writing the baseline report was from 01/01/1991 to 30/04/2011, with data available at 15min intervals. The data availability was checked again when writing the 2013-14 report and additional data from 1980 to 1990, at hourly intervals and the 15min data from April 2011 to January 2014 was downloaded and added to the project SANDS database. The data from February 2014 to March 2017 has since been added for each annual report. All data were adjusted from Chart Datum to Ordnance datum when imported to SANDS.

*Table 2-8 Predicted tide levels at Whitby*

| Tidal State | Level (m Chart Datum) | Level (m Ordnance Datum) |
|---|---|---|
| HAT | 6.21 | 3.21 |
| MHWS | 5.59 | 2.59 |
| MHWN | 4.50 | 1.50 |
| MLWN | 2.25 | -0.75 |
| MLWS | 0.99 | -2.01 |
| LAT | 0.22 | -2.78 |
| Highest predicted 2013 | 6.03 | 3.03 |
| Lowest predicted 2013 | 0.41 | -2.59 |
| Highest predicted 2014 | 6.17 | 3.17 |
| Lowest predicted 2014 | 0.32 | -2.68 |
| Highest predicted 2015 | 6.21 | 3.21 |
| Lowest predicted 2015 | 0.28 | -2.72 |
| Highest predicted 2016 | 6.14 | 3.14 |
| Lowest predicted 2016 | 0.32 | -2.68 |
| Highest predicted 2017 | 5.97 | 2.97 |
| Lowest predicted 2017 | 0.48 | -2.52 |
| Highest predicted 2018 | 6.05 | 3.05 |
| Lowest predicted 2018 | 0.35 | -2.65 |

Note: Based on data from http://www.ntslf.org/tgi/portinfo?port=Whitby

The 15 highest water levels observed at Whitby are presented in descending order in Table 2-9. The maximum water level recorded in 2016 was 3.35mOD, which is the 16th highest.

*Table 2-9 Maximum observed water levels at Whitby NTSLF gauge*

| Date | Level (mOD) |
|---|---|
| 28/01/2014 15:00 | 4.7 |
| 05/12/2013 17:15 | 4.32 |
| 01/02/1983 18:00 | 3.61 |
| 06/12/2013 05:45 | 3.49 |
| 18/03/2007 15:15 | 3.48 |
| 07/10/1990 05:00 | 3.47 |
| 04/01/2014 18:00 | 3.46 |
| 09/02/1997 17:15 | 3.46 |
| 01/01/1995 15:30 | 3.46 |
| 15/11/2005 03:00 | 3.43 |
| 20/03/1988 17:00 | 3.42 |
| 07/10/2006 03:15 | 3.42 |
| 27/02/1990 17:00 | 3.39 |
| 20/09/2005 04:45 | 3.36 |
| 12/01/2009 16:45 | 3.35 |

Based on data from https://www.bodc.ac.uk/data/online_delivery/

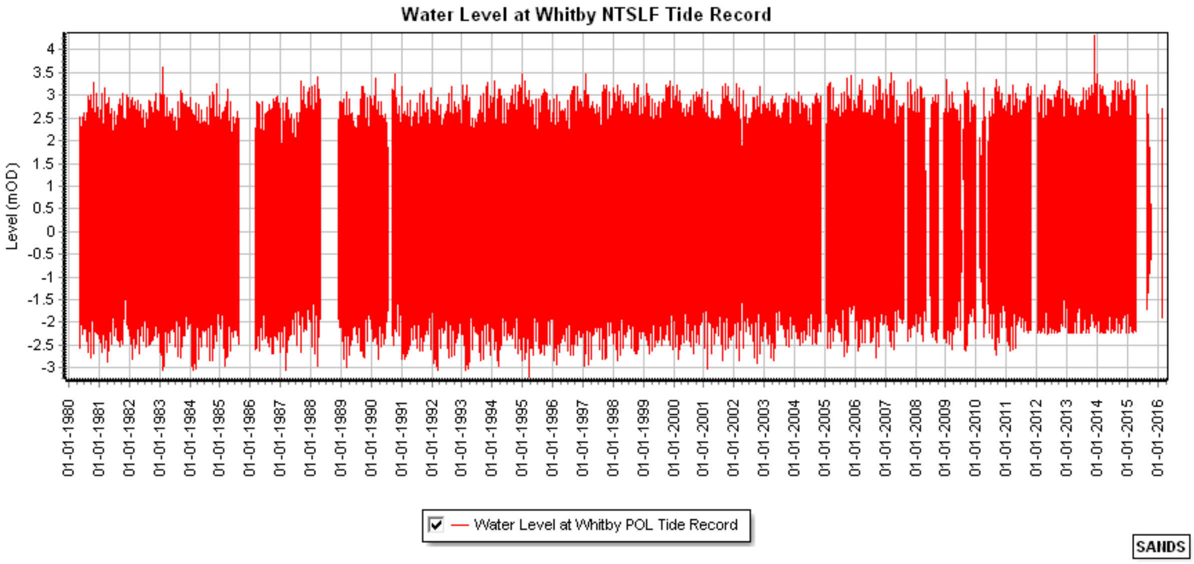



***Figure 2.10 Water Level data availability at Whitby NTSLF tide gauge site***

The data for Jan 2016 to March 2017 is largely flagged as suspect. The "usable data" covers the periods from 20th October to 20th December 2016, 17th January to 9th February 2017 and 27th February to 30th March 2017.

## 2.6. Whitby Harbour Tide Gauge

A tide gauge was deployed in Whitby by Fugro Emu for the Cell 1 regional monitoring programme during May 2013. Unfortunately there were problems with the deployment and the instrumentation such that reliable data was not received until early 2014. Data from this tide gauge was therefore first included in the Cell 1 report on wave and tide data for 2014/15.

The data set for 2016 was obtained from the Channel Coast Observatory (CCO) following their quality review and assessment of the data. The CCO report is included in Appendix E and the standard tidal heights they derived are presented in Table 2-10 below.

| Tidal levels | | |
|---|---|---|
| Observation period | January 2014 – July 2015 | |
| Tide Level | Elevation (OD) | Elevation (CD) |
| HAT | 3.14 | 6.14 |
| MHWS | 2.52 | 5.52 |
| MHWN | 1.41 | 4.41 |
| MLWN | -0.79 | 2.21 |
| MLWS | -1.91 | 1.09 |
| LAT | -2.91 | 0.09 |

***Table 2-10 Standard tidal levels at Whitby Harbour Tide Gauge (CCO, 2016)***

The highest water level recorded with the Whitby Harbour Tide Gauge in 2016 was 3.15mOD on19th September 2016.

The data from the two Whitby tide gauges has been compared by plotting the data together. An example for a short period in 2014 is shown in Figure 2.11. As noted in the 2014/15 report, comparing the derived standard tidal level data in Table 2-8 and Table 2-10, it is apparent that the levels recorded from the Cell 1 gauge are around 0.2m lower than those from the nearby

NTSLF gauge. Analysis of the two data sets from February to December 2014 revealed a mean difference of -0.18m and standard deviation of 0.02m. This takes account of concurrent measurements only and ignores gaps. The NTSLF gauge did not record (or had flagged quality issues for) levels for low water on the larger spring tides, which is discussed further in Sections 3.4 and 4.2. Some of the lowest tides are also not picked up by the Cell 1 gauge.

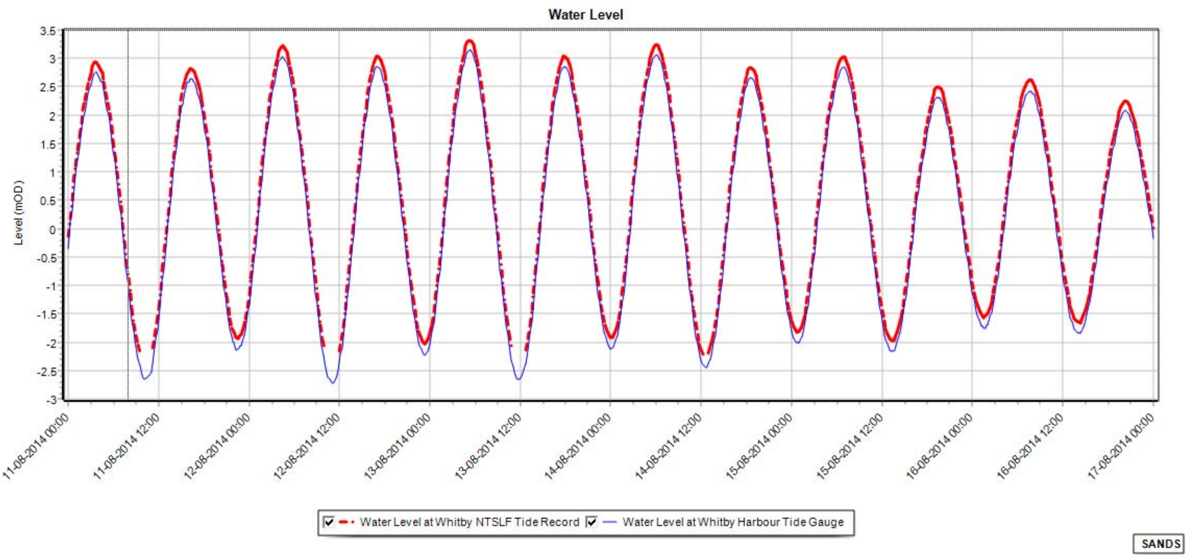



***Figure 2.11 Example comparison of water level data from Whitby tide gauges***

The reason for the 0.18m difference between the recorded levels remains uncertain but appears most likely to relate to differences between the datum surveys for the two sites. Noting the issues with long term level change in the NTSLF data it appears possible that there has been a datum shift of the NTSLF gauge and it is recommended that both gauges are resurveyed to resolve the issue. At the time of writing this report there are no current plans to address the issues at the NTSLF gauge in the short term, however in the long term ideally the Environment Agency would like to replace the gauge.

## 2.7. Scarborough Waverider Buoy

**Baseline data**

At Scarborough, data from the Waverider buoys deployed by Cefas and Emu (labelled as SBC and DWR wave buoys) were considered in the baseline report. These were located about 2.8 and 4.8 km offshore respectively. The data record reviewed at the original Emu DWR wave buoy runs from April 2004 to March 2006 and the record for the Cefas SBC buoy runs from April 2003 to July 2004. Scatter tables and wave roses were produced for both datasets using full years of data and these were for two and one year respectively. Storm and extremes analyses were carried out for the full record of the DWR wave data; the resulting figures and tables are shown in the sub-sections below.

**New data**

Under the latest phase of the programme, a Waverider buoy was deployed by Fugro-Emu offshore from Scarborough on 17$^{th}$ January 2013 at 54˚17.460'N, 000˚21.000'W. This is similar to the original SBC location. On 10$^{th}$ June 2013 the buoy was serviced and, following requests from fishermen, the buoy was moved to a further offshore location at 54˚17.605'N, 000˚19.082'W, which is similar to the previous DWR location. Details of the deployment are given in previous reports. Monthly plots of the data for April 2016 to March 2017 are included in Appendix D. There are several large gaps in the data set when buoy was off station due to damage. No data is available from25th May to 8$^{th}$ June 2016 or 6$^{th}$ November to 15$^{th}$ November 2016 or 16$^{th}$ March to 20$^{th}$ April 2017.

### 2.7.1. Wave height vs Wave Period

The distribution of the wave height and peak period for the baseline wave data record at Scarborough DWR and Scarborough SBC wave buoys has been plotted as a scatter plot (see

Figure 2.12 and Figure 2.13 below, respectively). The new data for the further offshore site has been overlaid on Figure 2.12 to compare to the baseline, and has also been plotted in Figure 2.14 to show fits for both peak and zero crossing period.

The new data plotted in Figure 2.12 covers the period from June 2013 to March 2017 and it is notable that the wave periods for the larger wave heights show a higher peak period than the baseline data. The 2016/17 data shows higher wave periods for the 0-2m and >4m wave height ranges than in previous years. The 2016/17 data includes the highest recorded wave heights (Hs) and zero crossing wave period (Tz). Comparing the blue 'baseline' 2003 to 2006 data to the new data from the current programme, there appears to be an issue with some of the wave period data in the earlier data set. The lower peak in periods for wave heights greater than 4.5m suggests that although the baseline data set was indicated to be peak period, Tp, some of the records may actually be Tmo (Tz). The wave height to period relationship for the baseline data set should therefore be treated with caution.

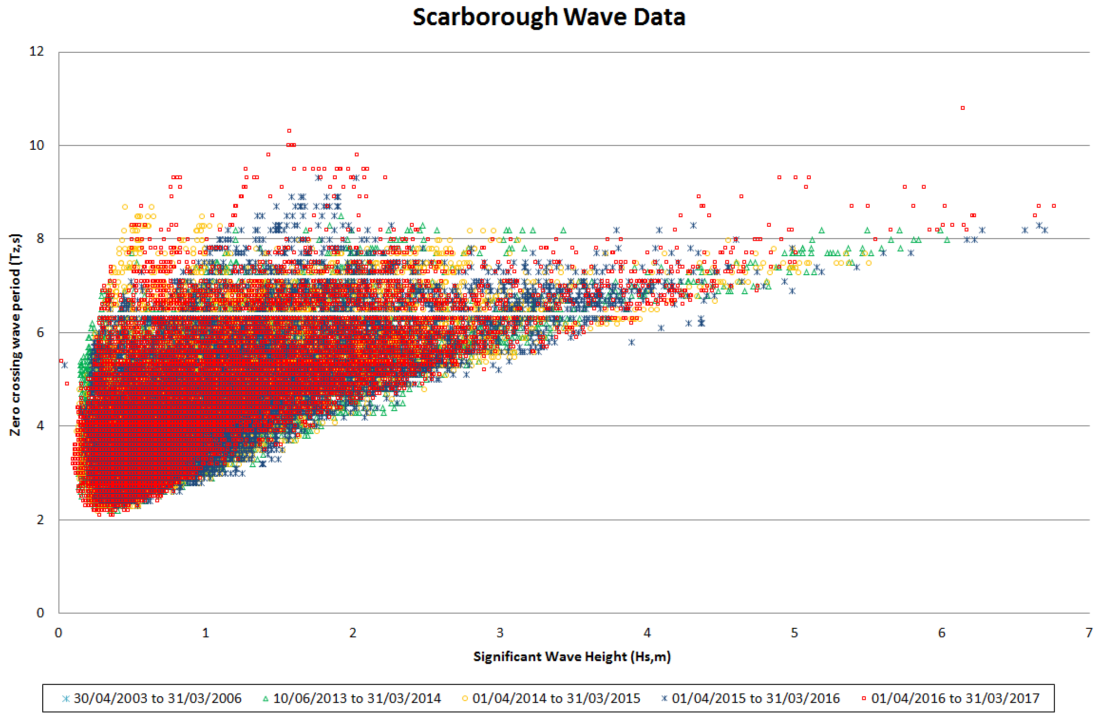



Figure 2.12 Scatter plot of Wave Height Vs Peak Period offshore Scarborough

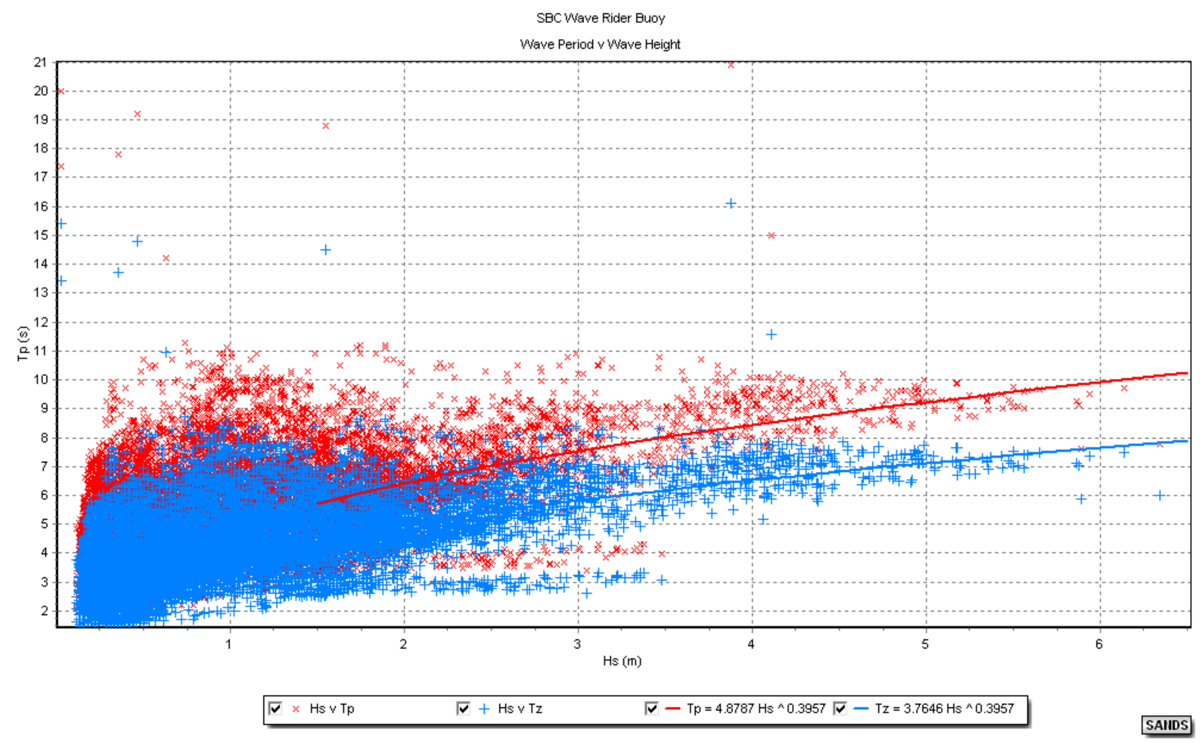



***Figure 2.13 Scatter plot Wave Height Vs Period at Scarborough SBC site (April 2003 to April 2004)***

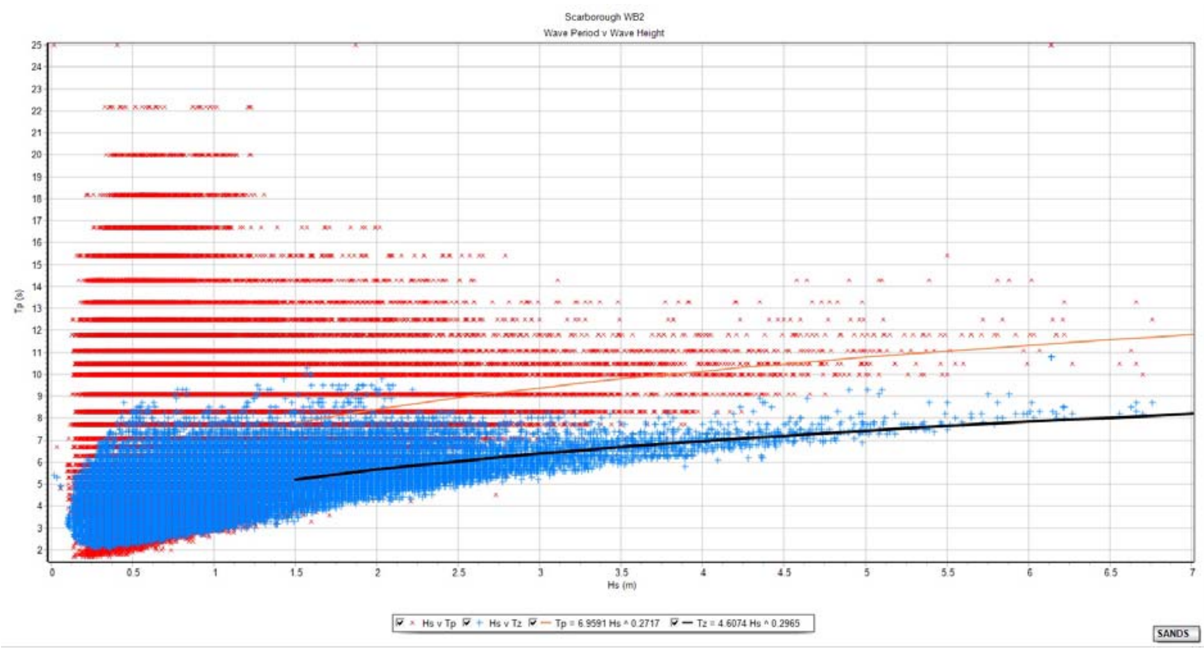



***Figure 2.14 Scatter plot Wave Height Vs Period at Scarborough WB2 site (June 2013 to March 2017)***

## 2.7.2. Wave Rose

The wave rose analysis of the baseline Scarborough DWR and SBC Waverider datasets (Figure 2.15 and Figure 2.16 respectively) show that the majority of the waves come from the north to northeast (0-30 degrees). The SBC dataset also shows a secondary wave direction from 105 to 120 degrees. This is interesting as the DWR buoy is further offshore and so might have been expected to have a wider spread of directions. It may be that the wider direction spread is made more apparent at the closer inshore location as it is slightly more sheltered from waves from the north, but alternatively the difference is more likely to reflect the different conditions occurring during the two time periods analysed.

A wave rose for the new data collected from the current, further offshore, location known as Scarborough WB2 is given in Figure 2.17. All three wave roses show fairly similar distributions, with most storms from 0 to 30 degrees and a secondary direction of 105 to 135 degrees.

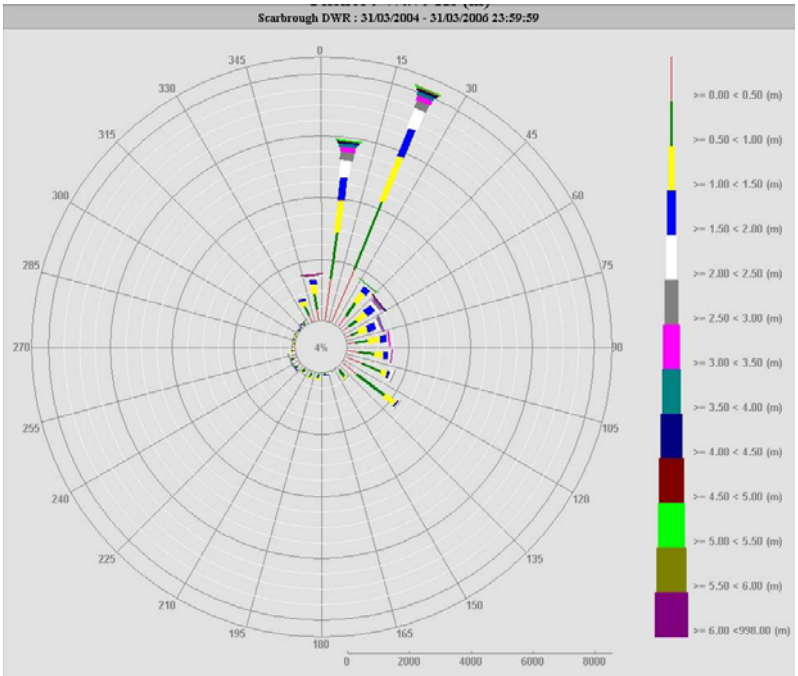



*Figure 2.15 Wave Rose at Scarborough DWR site*

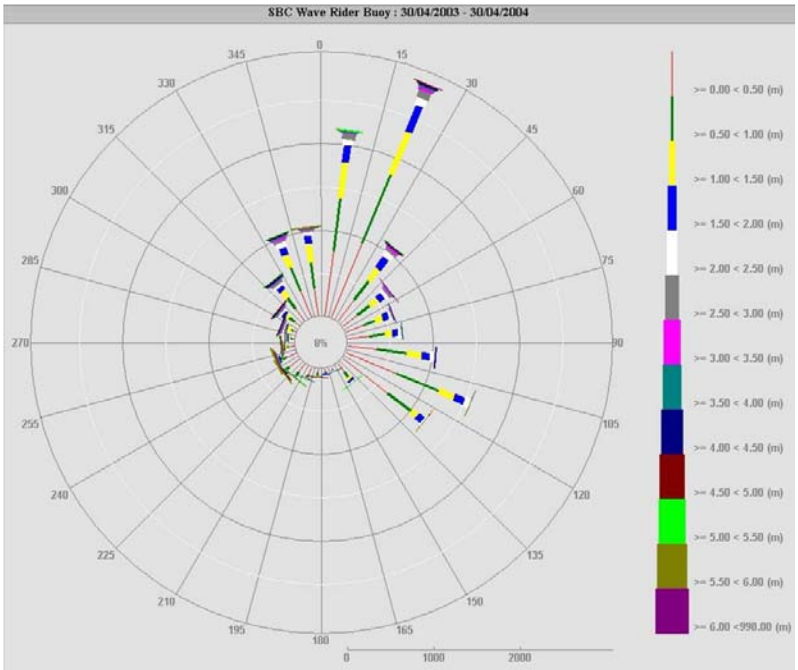



*Figure 2.16 Wave Rose at Scarborough SBC site*

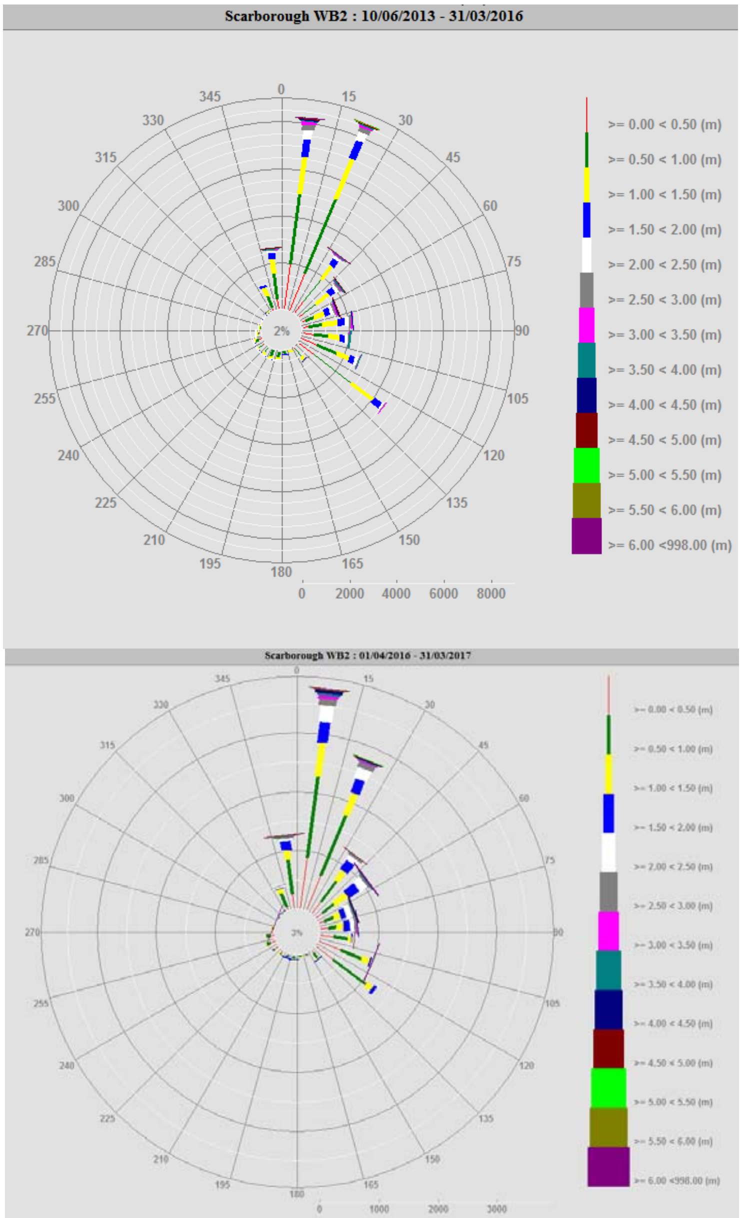



***Figure 2.17 Wave Rose at Scarborough WB2 site (June 2013 to March 2017)***

### 2.7.3. Storm Analysis

A storm analysis was carried out on the Scarborough DWR wave data (between 30/04/2003 and 31/03/2006), using a storm separation threshold of 120 hours and a wave height threshold of 4m. The results are shown in Table 2-11 below.

As with the Tyne Tees analysis, alternate years have been shaded, the largest storm Hs each year **is highlighted in bold** and the largest wave energy at storm peak **highlighted in bold red**. Note that only 2004 and 2005 are complete years so the conclusions that can be drawn from this analysis are limited. The largest recorded wave height at the storm peak was 6.3m on 28th January 2004. The largest wave energy at peak occurred on 25th November 2005.

Storms analysis from the new Waverider buoy deployed offshore from Scarborough as part of the current programme in January 2013 is provided in Table 2-12 below. This uses the full data set, ignoring the change of location in June 2013. The storm with the highest energy at peak was the January 2017 storm. It should be noted that the buoy was off station during the early December 2013 storm and to clarify a note has been added in the table below.

***Table 2-11 Storm analysis for Scarborough DWR wave buoy – baseline info***

| General Storm Information | | | | | | | At Peak | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Start Time** | **End Time** | **Dur (Hs)** | **Peak of Storm[1]** | **Mean Dir (°)** | **No of Events (30 min dataset)** | **Mean Dir Vector (°)** | **Hs (m)** | **Tp (s)** | **Dir (°)** | **Energy @ Peak (KJ/m/s)** |
| 14/12/2003 20:05 | 15/12/2003 20:35 | 25 | 15/12/2003 01:05 | 197 | 44 | 100.2 | 5.2 | 8.7 | 13 | 2808.3 |
| **21/12/2003 06:05** | **22/12/2003 08:05** | **26** | **21/12/2003 10:05** | **205** | **52** | **198.0** | **6.1** | 8.7 | **18** | **3961.0** |
| **28/01/2004 14:05** | **29/01/2004 08:05** | **18** | **28/01/2004 14:05** | **281** | **19** | **121.2** | **6.3** | **6.5** | **56** | **2321.3** |
| 08/02/2004 11:35 | 08/02/2004 23:35 | 12 | 08/02/2004 14:35 | 227 | 22 | 190.1 | 5.8 | 7.6 | 242 | 2123.2 |
| 22/02/2004 13:05 | 27/02/2004 06:35 | 114 | 22/02/2004 14:05 | 177 | 64 | 99.0 | 4.1 | 9.8 | 25 | 2233.6 |
| 12/11/2004 21:05 | 13/11/2004 01:35 | 4.5 | 12/11/2004 23:35 | 7 | 8 | 82.9 | 4.4 | 9.7 | 4 | **2467.5** |
| 23/01/2005 19:05 | 24/01/2005 09:35 | 15 | 24/01/2005 00:05 | 23 | 30 | 67.4 | 5.4 | 10.0 | 20 | 4047.8 |
| 19/02/2005 08:35 | 24/02/2005 14:05 | 126 | 24/02/2005 02:35 | 36 | 33 | 54.7 | 4.6 | 9.0 | 46 | 2363.1 |
| **08/04/2005 05:05** | **09/04/2005 01:05** | **20** | **08/04/2005 11:05** | **15** | **40** | **74.9** | **5.6** | **11.0** | **16** | **5286.2** |
| 24/11/2005 18:35 | 26/11/2005 10:05 | 40 | 25/11/2005 03:05 | 22 | 40 | 76.2 | 4.5 | 20.2 | 22 | **11368.1** |
| 16/12/2005 10:36 | 17/12/2005 18:35 | 32 | 16/12/2005 11:36 | 18 | 56 | 72.5 | 4.7 | 13.9 | 11 | 5799.2 |
| **08/02/2006 21:35** | **10/02/2006 00:35** | **27** | **09/02/2006 16:35** | **21** | **54** | **68.9** | **5.2** | **10.2** | **16** | **3920.2** |
| 28/02/2006 11:35 | 01/03/2006 00:05 | 13 | 28/02/2006 22:05 | 11 | 11 | 79.4 | 4.0 | 9.9 | 8 | 2183.3 |

Notes: [1] The time of the storm peak is based on peak wave energy, which is calculated in SANDS using $E = \rho.g.H_s^2.L_o/8$, with the offshore wave length $L_o = g.Tp^2/2.\pi$

***Table 2-12 Storm analysis for Scarborough WB (data 17/01/2013 to 31/03/2017)***

| General Storm Information | | | | | | | At Peak | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Start Time | End Time | Dur (hr) | Peak of Storm | Mean Dir | No of Events | Mean Direction Vector | Hs (m) | Tp (s) | Tz (s) | Dir | Energy @ Peak (KJ/m/s) | Total Energy (KJ/m) |
| 21/01/2013 02:00 | 21/01/2013 20:00 | 18 | 21/01/2013 13:00 | 68 | 35 | 22 | 5.1 | 11.1 | 7.8 | 65 | 6.4E+03 | 4.5E+06 |
| 06/02/2013 13:30 | 07/02/2013 02:00 | 12.5 | 06/02/2013 17:00 | 14 | 15 | 77 | 4.3 | 11.1 | 7.4 | 17 | 4.5E+03 | 1.7E+06 |
| 22/03/2013 20:00 | 24/03/2013 23:00 | 51 | 23/03/2013 15:30 | 74 | 99 | 16 | 5.1 | 11.8 | 7.7 | 65 | 7.1E+03 | 1.4E+07 |
| 23/05/2013 21:30 | 24/05/2013 10:30 | 13 | 24/05/2013 00:30 | 19 | 27 | 71 | 5.7 | 11.8 | 8.5 | 18 | 9.0E+03 | 4.9E+06 |
| 10/09/2013 13:00 | 10/09/2013 22:30 | 9.5 | 10/09/2013 19:30 | 13 | 19 | 77 | 5.0 | 10.0 | 7.3 | 13 | 4.9E+03 | 2.3E+06 |
| **10/10/2013 02:00** | **11/10/2013 06:30** | **28.5** | **10/10/2013 23:00** | **28** | **56** | **72** | **5.8** | 12.5 | **8.0** | **21** | **1.1E+04** | **1.1E+07** |
| **Data missing for 5th / 6th December 2013 storm as buoy was off station from 21st November 2013 until 17th December 2013** | | | | | | | | | | | | |
| 14/10/2014 03:00 | 14/10/2014 06:00 | 3 | 14/10/2014 04:30 | 61 | 4 | 33 | 4.4 | 9.1 | 6.7 | 61 | 3.2E+03 | 3.2E+05 |
| 31/01/2015 14:30 | 01/02/2015 18:30 | 28.0 | 31/01/15 23:30 | 20 | 57 | 76.74 | 4.8 | 13.3 | 7.5 | 25 | 8.0 E+3 | 8.2 E+6 |
| **21/11/2015 04:30** | **21/11/2015 16:30** | **12.0** | **21/11/15 09:30** | **11** | **22** | **79.62** | **6.2*** | **11.8** | **8.0** | **11** | **1.1 E+4** | **4.2 E+6** |
| **03/01/2016 06:00** | **06/01/2016 13:00** | **79.0** | **06/01/16 03:00** | **68** | **26** | **26.05** | **5.0** | **10.5** | **7.8** | **65** | **5.4 E+3** | **2.9 E+6** |
| 14/01/2016 14:00 | 16/01/2016 06:00 | 40.0 | 16/01/16 05:00 | 100 | 15 | 81.32 | 4.2 | 11.8 | 7.5 | 13 | 4.9 E+3 | 1.5 E+6 |
| **13/01/2017 10:30** | **14/01/2017 04:00** | **17.5** | **13/01/17 14:00** | **152** | **34** | **99.0** | **9.0** | **25.0** | **11.1** | **290** | **9.98 E+4** | **1.20 E+7** |
| 12/02/2017 02:00 | 12/02/2017 20:30 | 18.5 | 12/02/17 05:30 | 63 | 31 | 27.9 | 4.9 | 10.0 | 7.4 | 55 | 4.73 E+3 | 3.14 E+6 |
| 23/02/2017 18:00 | 23/02/2017 21:00 | 3.0 | 23/02/17 19:30 | 136 | 5 | 86.4 | 4.5 | 10.0 | 7.3 | 4 | 3.96 E+3 | 4.31 E+5 |

## 2.8. Scarborough Tide Gauge

The Scarborough tide gauge was deployed by Emu on behalf of SBC in April 2003 as part of a local monitoring initiative prior to the start of the regional programme. The data runs from 28/04/2003 to 30/4/2017, with a number of gaps in the record. A detailed plot showing the data available for 2016 is shown in Figure 2.18.

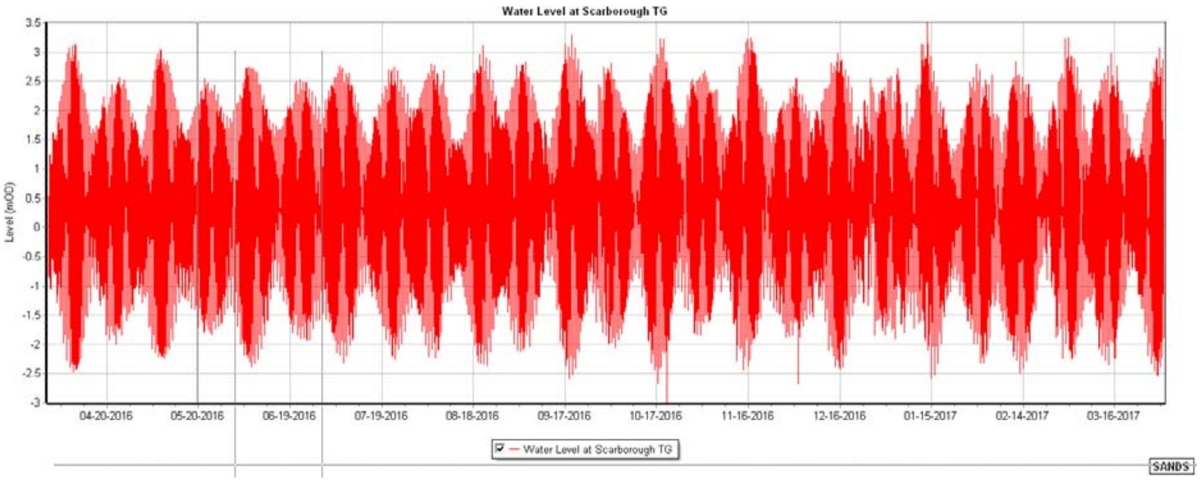



***Figure 2.18 Water Levels at Scarborough TG Recorded Tide Site for 2016-17***

The Scarborough tide gauge data has been analysed and quality controlled by Fugro-EMU and Channel Coast Observatory. The CCO report is included in Appendix E and standard tidal heights are presented in Table 2-13 below.

It should be noted that when the site was checked and re-surveyed by Fugro-EMU in June 2013, a discrepancy was found compared to the original datum established in 2003, with the tide gauge zero now 0.195m higher than previously assumed. It is not known when the offset applies from, but Fugro-EMU noted in 2013 that *"this offset brings the data back in line with predictions created through the harmonic analysis of the data from 2003 and also predictions created from the Admiralty harmonic constants for Scarborough."*

***Table 2-13 Standard tidal levels at Scarborough***

| Tidal levels | | |
|---|---|---|
| Observation period | January 2013 – October 2014 | |
| Tide Level | Elevation (OD) | Elevation (CD) |
| HAT | 3.34 | 6.59 |
| MHWS | 2.52 | 5.77 |
| MHWN | 1.38 | 4.63 |
| MLWN | -0.86 | 2.39 |
| MLWS | -2.00 | 1.25 |
| LAT | -3.02 | 0.23 |

Notes: Source – CCO report for 2015 data, see Appendix E
See also note above re-potential issues with datum for 2006 to 2011 data.

Annual maxima water levels extracted from the Scarborough tide gauge are shown in Table 2-14 below. The highest recorded water level in 2013 was 4.39 mOD on 5th December 2013 at 17:20, and had an associated surge of 1.66m. This is significantly higher than any of the previous 10 years, the maximum of which was 3.66m in January 2005.

***Table 2-14 Annual maxima data from Scarborough Tide gauge (source CCO, 2016)*[1]**

| Year | Annual extreme maxima | | Annual surge maxima | | $Z_0$ (OD) | Annual recovery rate |
|---|---|---|---|---|---|---|
| | Elevation (OD) *(Surge)* | Date/Time | Value (m) | Date/Time | | |
| 2003 | 3.05 *(-0.03)* | 28-Sep-2003 05:10 | 1.13 | 21-Dec-2003 09:40 | - | 76% |
| 2004 | 3.09 *(0.34)* | 22-Feb-2004 17:10 | 0.96 | 18-Nov-2004 04:00 | 0.292 | 99% |
| 2005 | 3.66 *(0.86)* | 12-Jan-2005 17:20 | 1.18 | 20-Jan-2005 08:20 | 0.287 | 99% |
| 2006* | 3.30 *(0.17)* | 30-Mar-2006 16:30 | 1.29 | 31-Oct-2006 15:40 | - | 77% |
| 2007* | 3.40 *(0.71)* | 25-Nov-2007 04:00 | 1.60 | 08-Nov-2007 21:30 | 0.221 | 97% |
| 2008* | 3.05 *(0.16)* | 09-Mar-2008 17:20 | 0.90 | 22-Feb-2008 02:10 | - | 65% |
| 2009* | 3.19 *(0.44)* | 12-Jan-2009 16:50 | 1.15 | 18-Jan-2009 16:30 | - | 84% |
| 2010* | 3.21 *(0.05)* | 11-Sep-2010 05:30 | 0.81 | 12-Nov-2010 04:20 | - | 82% |
| 2011* | 3.03 *(-0.14)* | 21-Mar-2011 17:10 | 1.33 | 04-Feb-2011 11:00 | - | 80% |
| 2012 | 2.94 *(0.06)* | 17-Oct-2012 04:40 | 0.92 | 05-Jan-2012 16:40 | - | 70% |
| 2013 | 4.39 *(1.66)* | 05-Dec-2013 17:20 | 1.75 | 05-Dec-2013 15:50 | 0.186 | 98% |
| 2014 | 3.40 *(0.51)* | 04-Jan-2014 18:00 | 1.16 | 21-Oct-2014 20:20 | | 88% |
| 2015 | 3.29 *(0.29)* | 21-Feb-2015 17:40 | 1.23 | 10-Jan-2015 17:30 | - | 98% |

* Possible datum shift by up to -0.195m

[1] CCO February 2016, Scarborough tide gauge annual report, see Appendix E

# 3. Problems encountered and uncertainty in analysis

## 3.1 Wave data

As noted in the report, the Scarborough Waverider buoy was moved to a new location after the initial deployment. Although the locations used are the same as two previous wave buoys the different water depths and coastal sheltering means that the new data from the two sites are not directly comparable.

The Tyne Tees wave data is available in both telemetry and post recovery format from the Cefas WaveNet site. At the time of writing post-recovery data were available up to November 2016. However, there were two significant gaps in the post-processed data (21/01/2008 to 08/04/2009 and 19/02/2014 to 12/05/2014) that were filled by telemetry data as well as from November 2016. The data set analysed is therefore a combination of telemetry and post recovery data, to give greatest coverage.

The Scarborough Waverider was off station due to several incidents during the year and no data are available from 6th to 15th November 2016 or 16th March to 20th April 2017.

## 4.2 Water level data

The data for Jan 2016 to March 2017 is largely flagged as suspect. The “usable data” covers periods from 20th October to 20the December 2016, 17th January to 9th February 2017 and 27th February to 30th March 2017.

The quality controlled data from BODC for the Whitby NTSLF tide gauge shows that much of the data for 2015-16 has been flagged as suspect due to issues with the gauge including siltation, the recording of flat low waters and an unexplained high rate of mean sea level rise. The issue with the datum difference compared to the Cell 1 programme Whitby Harbour tide gauge noted in last years’ report remains under investigation.

As noted in the baseline report there is uncertainty over datum changes for the Scarborough tide gauge between the original deployment in 2003 and the site checks in 2013, with a discrepancy of 0.195m. The data has been quality checked by CCO since the baseline report, but this uncertainty still remains. The data for November 2014 is missing from the record. During 2015 there was a gap in the data from the Scarborough tide gauge of 29th June to 3rd July 2015.There are no significant gaps in the data for 2016 and early 2017.

The consideration of variability and trends in the longer term data sets highlighted problems with the Whitby NTSLF tide gauge and a datum issue compared to the Cell 1 Whitby gauge. In addition to gaps in the data there is missing data on the extreme low waters, see for example Figure 2.11.

It is recommended that the datum level surveys are checked for both of the Whitby tide gauges to establish which is correct and if possible the data should be corrected.

# 4. Summary of key findings and recommendations

This report has analysed new wave and water level data available relevant to coastal Cell 1 for 2016-2017 as an update to the previous baseline reports. Future reports in this series should compare the data recorded in subsequent years with the results presented here. The key points are summarised below:

- Offshore wave directions incident on the Cell 1 coast are predominantly between 0 and 30 degrees (north to northeast), with a secondary wave approach direction from the east to southeast also observed although some parts of the coast are more sheltered from fetches to the southeast.
- The Newbiggin Ness wave buoy site is partially sheltered from waves from the north. The data from 2016-17 is consistent with the data in 2013-15, but the wave rose is notably different to the baseline data from 2010-11 collected by Cefas, which did not show the secondary wave direction from the southeast.
- The longest consistent wave record in the region is for the Wavenet Tyne Tees buoy, which has been operating since late 2006.
- The Met Office offshore wave hindcast modelled data for 1980 to 2012 was shown to under-predict wave heights during storm events by up to 0.5m and so should be treated with caution if used for boundary conditions in modelling studies.
- Analysis of the 2006 to 2017 data from Tyne Tees indicates that the stormiest year was 2010 whilst the year with the least number of storms is 2011. Due to the limited period of data available from Newbiggin, Whitby and Scarborough it is not yet possible to make reliable comparisons to Tyne Tees.
- Although there were few storms during 2016-17 the largest wave height recorded to date at Newbiggin was on the 3rd Jan 2016 and largest to date at both Whitby and Scarborough was on the13th January 2017.
- The data sets have been reviewed to assess medium to long term changes and it has been demonstrated that the even the longest wave data set from Tyne Tees is of insufficient length to capture the annual storm variability demonstrated in the longer period of data available from the Met Office hindcast wave model.
- Analysis of the Cell 1 tide gauge located in Whitby Harbour has previously found that there is a datum issue with either or both Whitby tide gauges. The data from the national gauge is considered unreliable by NOC from April 2015 onwards. It is recommended that this is investigated further and new datum level surveys are undertaken for both gauges.

Wave roses for full datasets available for Newbiggin Ness, Whitby, and Scarborough are collated in Figure 5.1 to supplement the points made above. Wave height data over the period April 2016 to March 2017 for the four Cell 1 wave buoys are also shown in Figure 4.2 to illustrate the data availability.

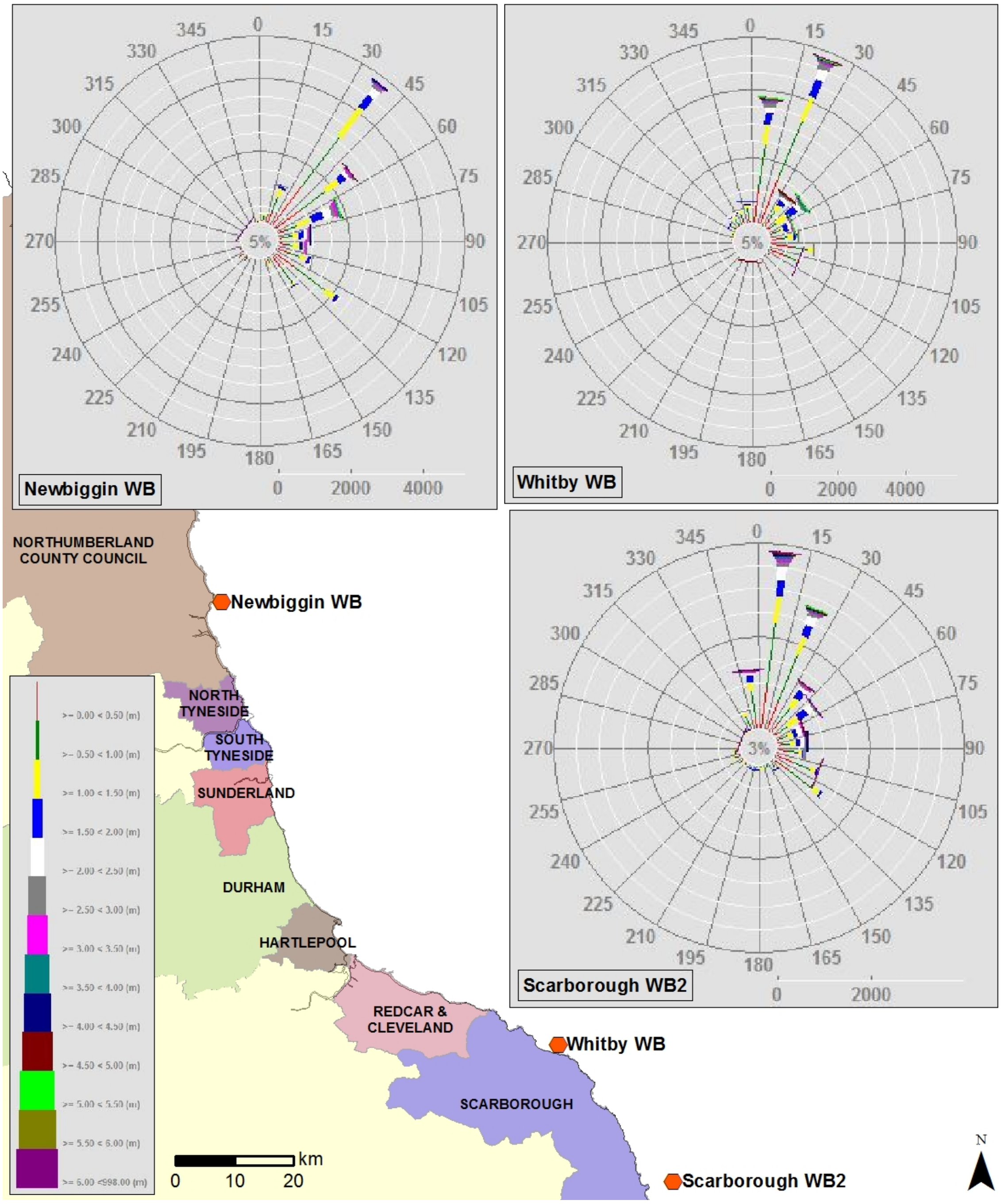



*Figure 4.1 Wave Rose Locations from Newbiggin Ness to Scarborough*

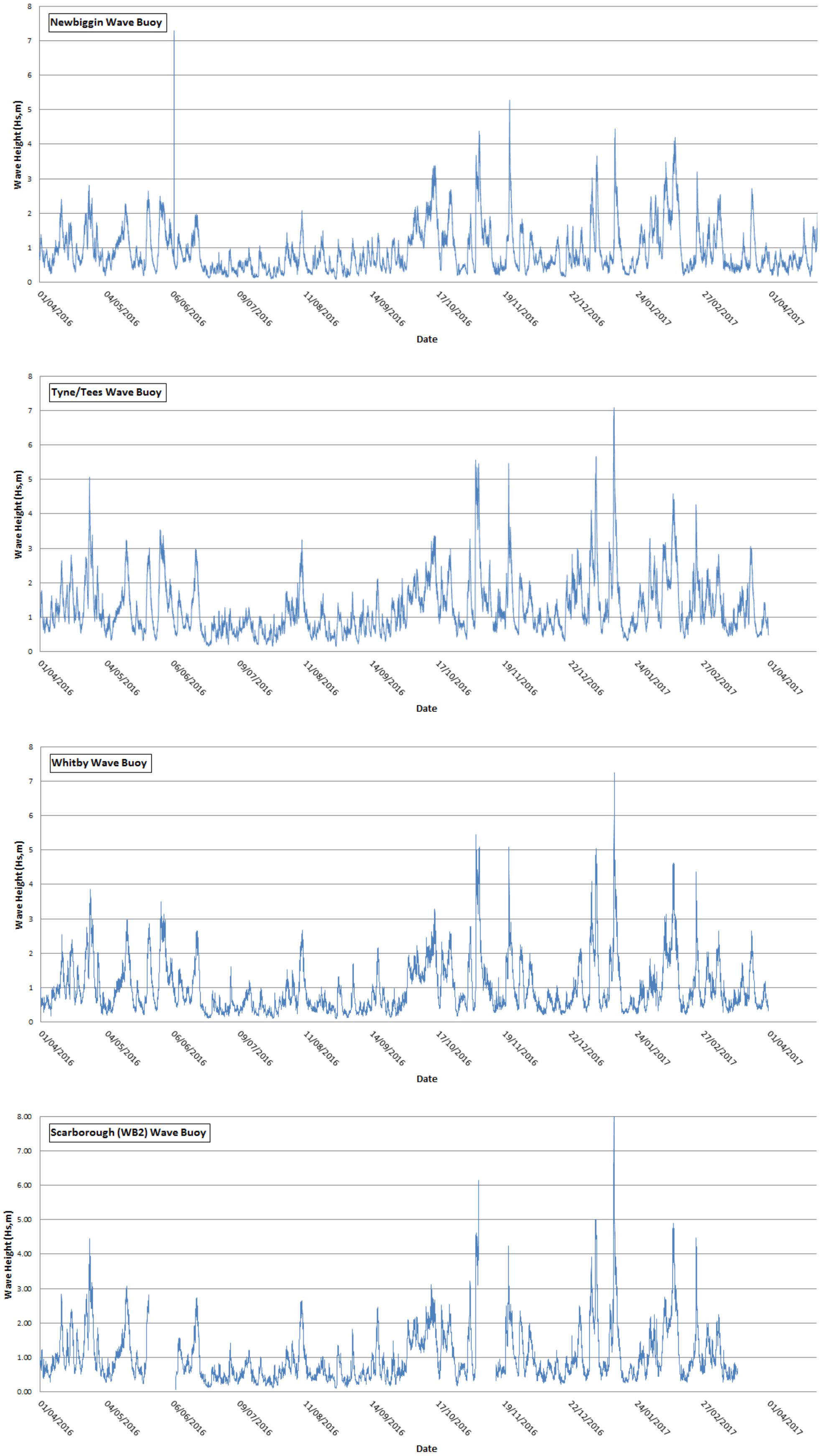



*Figure 4.2 Wave height data for 2016-17 in Cell 1*

# 5. Conclusions

This report has documented the annual review and analysis of wave and tide data across Cell 1, presenting analysis of the data sets collected at the three wave buoys that were deployed under the strategic monitoring programme at Newbiggin Ness, Whitby and Scarborough, alongside data from the Cefas buoy located at Tyne Tees that is operated as part of the national programme. Tide gauge data collected under the programme has also been analysed and compared to the data from the tide gauges at Whitby and North Shields that are operated as part of the national monitoring programme.

Although there were fewer storms in 2016-17 than in previous years, the largest wave heights recorded to date occurred in January 2016 at Whitby and Scarborough and in early January at Newbiggin. Wave conditions during the 2016/17 period were notably less stormy than in some of the previous years.

# Appendices

# Appendix A
# Detailed Location of Wave Buoys

# Appendix B
# Supporting Graphs: Newbiggin Wave Buoy

# Appendix C
# Supporting Graphs: Whitby Wave Buoy

# Appendix D
# Supporting Graphs: Scarborough Wave Buoy

# Appendix E

## Annual reports for:
## Scarborough and Whitby tide gauges, and
## Newbiggin, Whitby, and Scarborough wave buoys