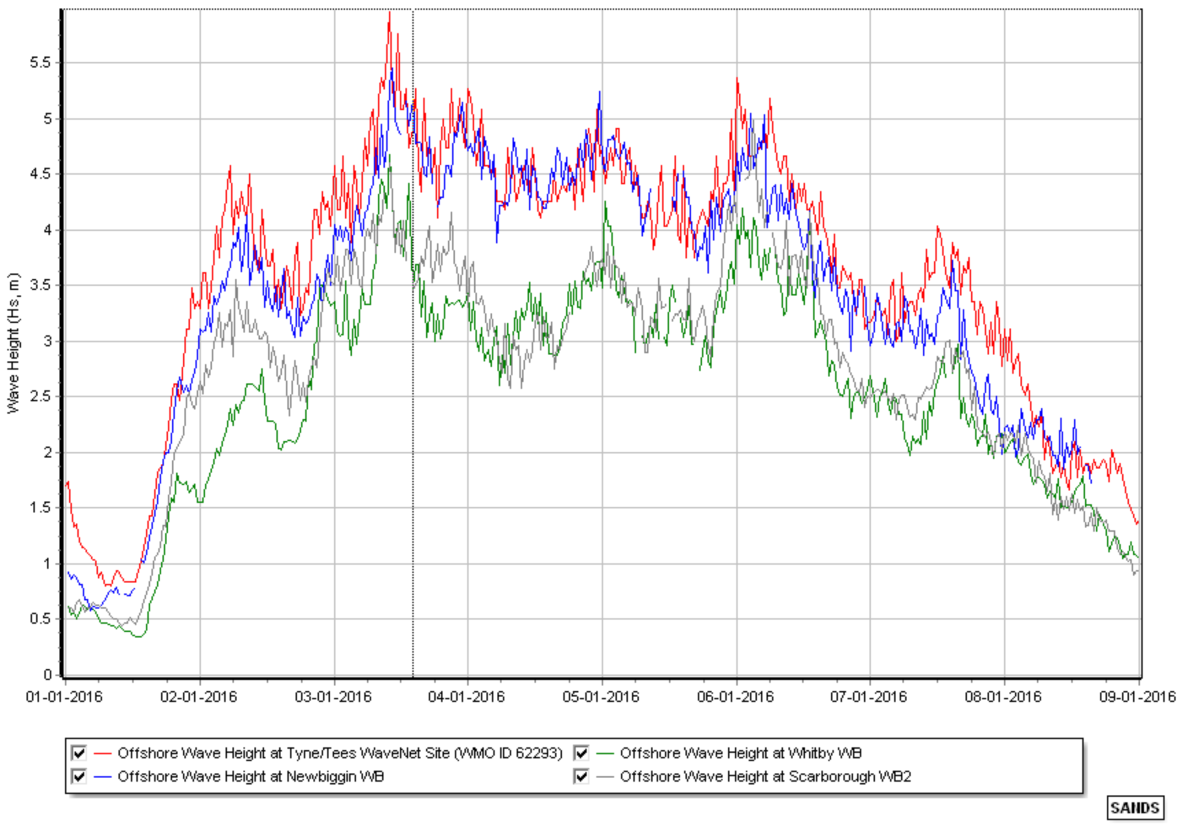


Measured wave heights in Cell 1 during the easterly storm in January 2016

Cell 1 Regional Coastal Monitoring Programme
Wave Data Analysis Report 4: 2015 - 2016

Final Report
June 2016

Contents

Disclaimer ... i
Abbreviations and Acronyms ... iii
Glossary of Terms ... iv
Preamble ... v
1. Introduction ... 1
1.1. Study background and scope ... 1
1.2. Study area and available wave and tide data ... 1
1.3. Methodology ... 3
1.4. Summary of new data available ... 4
2. Analysis of data ... 5
2.1. Newbiggin Ness Waverider Buoy ... 5
2.2. North Shields Tide gauge ... 9
2.3. Tyne Tees WaveNet Buoy ... 12
2.4. Whitby Waverider Buoy ... 22
2.5. Whitby NTSLF Tide Gauge ... 26
2.6. Whitby Harbour Tide Gauge ... 29
2.7. Scarborough Waverider Buoy ... 31
2.8. Scarborough Tide Gauge ... 37
3. Discussion of variability in waves and water levels and longer term trends ... 41
3.1. Data availability ... 41
3.2. North Shields tide record ... 42
3.3. Tyne / Tees Wavenet site ... 44
3.4. Whitby tide record ... 45
4. Problems encountered and uncertainty in analysis ... 46
5. Summary of key findings and recommendations ... 48
6. Conclusions ... 50

List of Figures

Figure 0.1 Sediment Cells in England and Wales ... v
Figure 1.1 Study Area and historical data sets reviewed in the baseline report, Halcrow 2013 ... 2
Figure 1.2 Updated data sets reviewed in this report ... 3
Figure 2.1 Scatter plot of Wave Height Vs Peak Period at Newbiggin wave buoy ... 5
Figure 2.2 Wave roses for Newbiggin WB original deployment in 2010/11 and new data for 2013/14, 2014/15 and 2015/16 ... 6
Figure 2.3 Plot of water level data availability at North Shields NTSLF Tide Gauge ... 10
Figure 2.4 Plot of water level data availability for 2015/16 at North Shields NTSLF Tide Gauge ... 10
Figure 2.5 Comparison of recorded and modelled wave heights at Tyne Tees in winter 2009 showing under-prediction of modelled data ... 13
Figure 2.6 Comparison of recorded wave heights at Tyne Tees to the Cell 1 programme buoys from April 2015 to March 2016 ... 14
Figure 2.7 Scatter plot of Wave Height Vs Peak Period at Tyne Tees wave buoy site ... 15
Figure 2.8 Wave Rose at Tyne Tees wave buoy site (WMO ID 62293) ... 16
Figure 2.9 Total storm energy and wave direction at the peak of each storm for Tyne Tees Wave Buoy ... 21
Figure 2.10 Storm duration, with Hs and Tz at peak for Tyne Tees Wave Buoy ... 21
Figure 2.11 Storm energy comparison for Met Office model and Tyne Tees Wave Buoy ... 22
Figure 2.12 Scatter plot of Wave Height Vs Zero crossing period at Whitby wave buoy site 23
Figure 2.13 Wave Roses at Whitby wave buoy site ... 24
Figure 2.14 Water Level data availability at Whitby NTSLF tide gauge site ... 28

Figure 2.15 Water Level data availability for 2015/16 at Whitby NTSLF tide gauge site, also showing the Cell 1 Whitby Harbour Tide Gauge 29
Figure 2.16 Example comparison of water level data from Whitby tide gauges 30
Figure 2.17 Scatter plot of Wave Height Vs Peak Period offshore Scarborough 32
Figure 2.18 Scatter plot Wave Height Vs Period at Scarborough SBC site (April 2003 to April 2004) 32
Figure 2.19 Scatter plot Wave Height Vs Period at Scarborough WB2 site (June 2013 to March 2016) 33
Figure 2.20 Wave Rose at Scarborough DWR site 34
Figure 2.21 Wave Rose at Scarborough SBC site 34
Figure 2.22 Wave Rose at Scarborough WB2 site (June 2013 to March 2016) 35
Figure 2.23 Water Levels at Scarborough TG Recorded Tide Site 37
Figure 2.24 Water Levels at Scarborough TG Recorded Tide Site for 2015-16 38
Figure 3.1 Annual and monthly mean sea level data for North Shields, 1895 to 2015 43
Figure 3.2 Tide gauge GPS monitoring data from BIGF for station nstg/nslg 44
Figure 3.3 Annual maximum wave height from Met office model and Tyne Tees Buoy 45
Figure 3.4 Annual and monthly mean sea level data for Whitby, 1980 to 2015 46
Figure 5.1 Wave Rose Locations from Newbiggin Ness to Scarborough 49
Figure 5.2 Wave height data for 2015-16 in Cell 1 50

List of Tables

Table 1-1 List of updated datasets available for the 2015 to 2016 report 4
Table 2-1 Storm analysis for Newbiggin Ness (20/05/2010 to 07/06/2011) 7
Table 2-2 Storm analysis for Newbiggin WB (data 21/06/2013 to 31/03/2016) 8
Table 2-3 Predicted tide levels at North Shields 9
Table 2-4 Maximum observed water levels at North Shields 11
Table 2-5 Predicted extreme tide levels at North Shields 12
Table 2-6 Wave Height and Direction Scatter Table for Tyne Tees WaveNet Site 16
Table 2-7 Wave Period and Direction Scatter Table for Tyne Tees WaveNet Site 17
Table 2-8 Extremes Analysis for Tyne Tees buoy 17
Table 2-9 Storm Analysis at Tyne Tees WaveNet Buoy (data to 31st March 2016) 18
Table 2-10 Scatter table for Tyne Tees WaveNet data vs North Shields water levels 22
Table 2-11 Storm Analysis results for Whitby – Baseline data 20/05/2010 to 25/10/2011 ... 24
Table 2-12 Storm analysis for Whitby WB (data 17/01/2013 to 31/03/2016) 25
Table 2-13 Predicted tide levels at Whitby 26
Table 2-14 Maximum observed water levels at Whitby NTSLF gauge 27
Table 2-15 Predicted extreme tide levels at Whitby 28
Table 2-16 Scatter table of water level and offshore wave height at Whitby 29
Table 2-17 Standard tidal levels at Whitby Harbour Tide Gauge (CCO, 2015) 30
Table 2-18 Extremes Analysis for Scarborough wave buoys 35
Table 2-19 Storm analysis for Scarborough DWR wave buoy – baseline info 36
Table 2-20 Storm analysis for Scarborough WB (data 17/01/2013 to 31/03/2016) 37
Table 2-21 Standard tidal levels at Scarborough 38
Table 2-22 Annual maxima data from Scarborough Tide gauge (source CCO, 2016) 39
Table 2-23 Predicted extreme tide levels at Scarborough 40
Table 2-24 Scatter table of water level and wave height at Scarborough 40
Table 3-1 Duration of data sets in Cell 1 and comments on reliability 41

Appendices

Appendix A Detailed location of wave buoys
Appendix B Supporting graphs: Newbiggin Ness wave buoy
Appendix C Supporting graphs: Whitby wave buoy
Appendix D Supporting graphs: Scarborough wave buoy
Appendix E CCO Annual reports for Scarborough and Whitby tide gauges and Newbiggin, Whitby and Scarborough wave buoys

Scarborough Borough Council
Cell 1 Wave and Tide data Report 2015 – 16

Contents Amendment Record

This report has been issued and amended as follows:

Issue	Revision	Description	Date	Authors
1	0	Draft Final	May 2016	A Parsons original draft Paul Fish reviewer
1	1	Final	June 2016	A Parsons

Disclaimer

Halcrow Group Limited ('Halcrow') is a CH2M company. Halcrow has prepared this report in accordance with the instructions of our client Scarborough Borough Council (SBC) for the client's sole and specific use. Any other persons who use any information contained herein do so at their own risk. This report is a review of coastal survey information made available by SBC. The objective of this report is to provide an assessment and review of the relevant background documentation and to analyse and interpret the coastal monitoring data. Halcrow has used reasonable skill, care and diligence in the interpretation of data provided to them and accepts no responsibility for the content, quality or accuracy of any Third party reports, monitoring data or further information provided either to them by SBC or, via SBC from a Third party source, for analysis under this term contract.

Raw data analysed in this report is available to download via the project's webpage: www.northeastcoastalobservatory.org.uk. The North East Coastal Observatory does not "license" the use of images or data or sign license agreements. The North East Coastal Observatory generally has no objection to the reproduction and use of these materials (aerial photography, wave data, beach surveys, bathymetric surveys), subject to the following conditions:

1. North East Coastal Observatory material may not be used to state or imply the endorsement by North East Coastal Observatory or by any North East Coastal Observatory employee of a commercial product, service, or activity, or used in any manner that might mislead.

2. North East Coastal Observatory should be acknowledged as the source of the material in any use of images and data accessed through this website, please state "Image/Data courtesy of North East Coastal Observatory". We recommend that the caption for any image and data published includes our website, so that others can locate or obtain copies when needed. We always appreciate notification of beneficial uses of images and data within your applications. This will help us continue to maintain these freely available services. Send e-mail to Robin.Siddle@scarborough.gov.uk

3. It is unlawful to falsely claim copyright or other rights in North East Coastal Observatory material.

4. North East Coastal Observatory shall in no way be liable for any costs, expenses, claims, or demands arising out of the use of North East Coastal Observatory material by a recipient or a recipient's distributees.

5. North East Coastal Observatory does not indemnify nor hold harmless users of North East Coastal Observatory material, nor release such users from copyright infringement, nor grant exclusive use rights with respect to North East Coastal Observatory material.

6. North East Coastal Observatory material is not protected by copyright unless noted (in associated metadata). If copyrighted, permission should be obtained from the copyright owner prior to use. If not copyrighted, North East Coastal Observatory material may be reproduced and distributed without further permission from North East Coastal Observatory.

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.

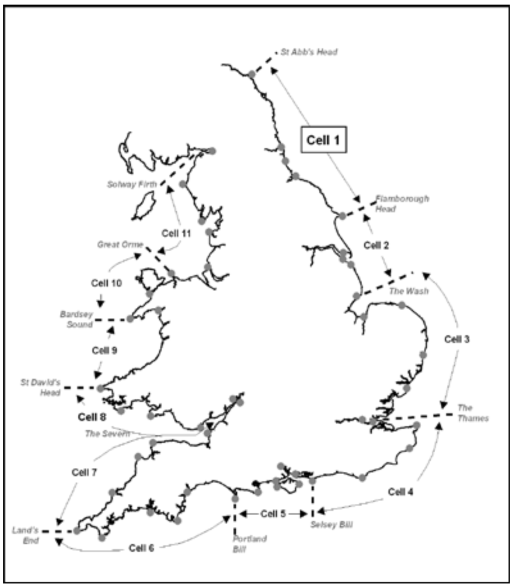


Figure 0.1 Sediment Cells in England and Wales

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:

Northumberland County Council
Northumberland Coast Area of Outstanding Natural Beauty
North Tyneside Council
South Tyneside Council
Sunderland City Council
Durham County Council
Redcar & Cleveland Borough Council
Hartlepool Borough Council
Whitby Scarborough Filey Borough of Scarborough – A great place to live, work & play
East Riding of Yorkshire Council
Environment Agency
Natural England
The National Trust

The original three year programme of work was undertaken as a partnership between Royal Haskoning, Halcrow and Academy Geomatics. For the current five year programme of work the data collection associated with beach profiles, topographic surveys and cliff top surveys is being undertaken by Academy Geomatics. The analysis and reporting for the programme is being undertaken by Halcrow.

Wave and tide data collection under the present phase of the programme started in January 2013. The data collection is being undertaken by Fugro Emu, and the new wave and tide data that is being collected is available in near real-time on both the Channel Coast Observatory website http://www.coastalmonitoring.org and the www.northeastcoastalobservatory.org.uk website developed for this programme.

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 and Tide Data Analysis Report 4.** This provides an update to the analysis presented in the baseline wave data report and compares the wave data collected between March 2015 and March 2016, to the baseline analysis in Wave Data Analysis Report 1 published in 2013 and updates in reports 2 and 3.

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 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 Data Analysis Report 4** and provides an analysis of the wave data collected during 2015-2016 as part of the programme. The report forms an update to and supersedes the baseline assessment in **Wave Data Analysis Report 1 (Halcrow, 2013),** and the update reports in **Wave Data Analysis Report 2 (Halcrow, 2014) and Wave Data Analysis Report 3 (CH2M, 2015)**. 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.

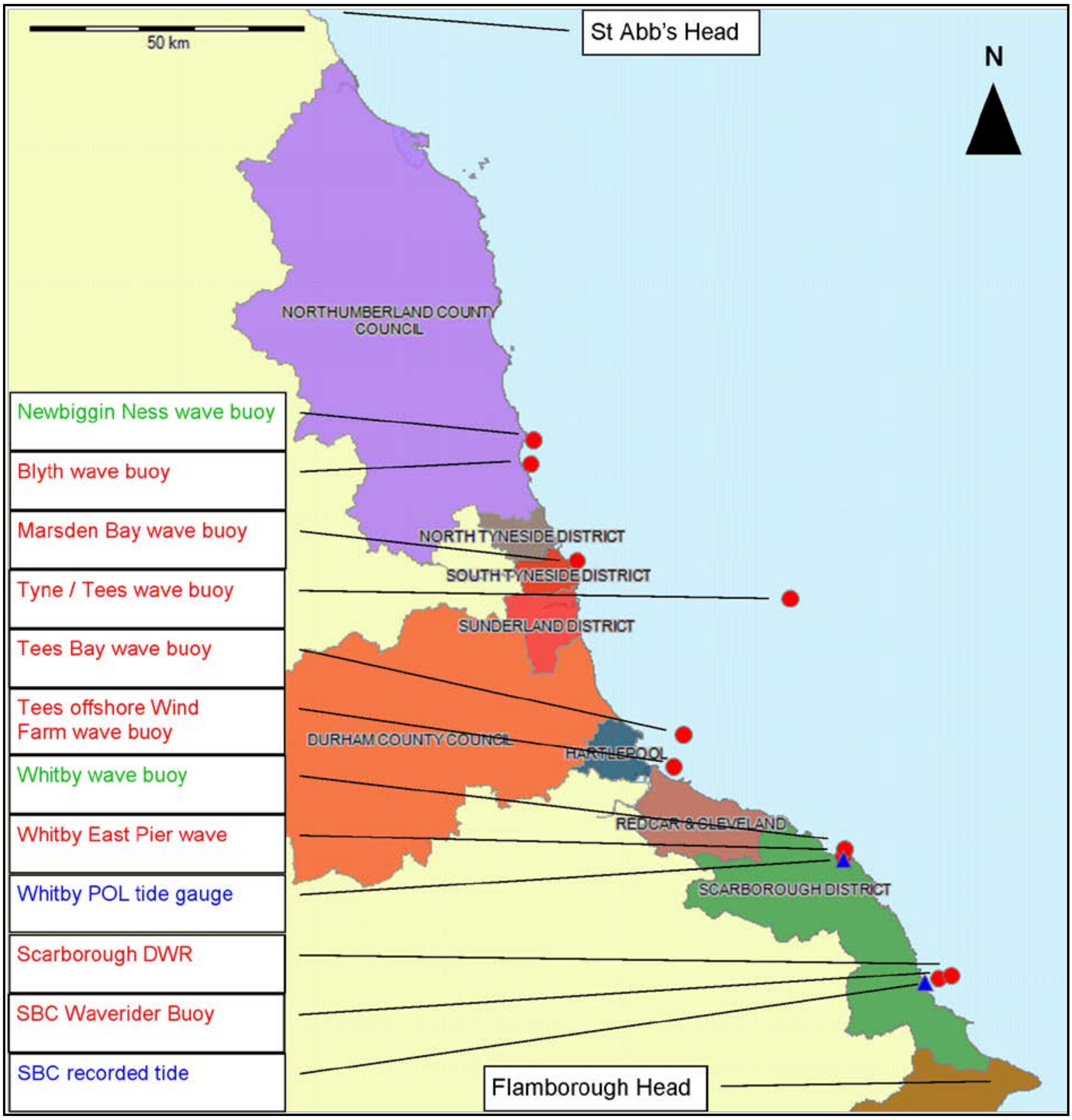
1.2. Study area and available wave and tide data

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 below.

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 below 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)

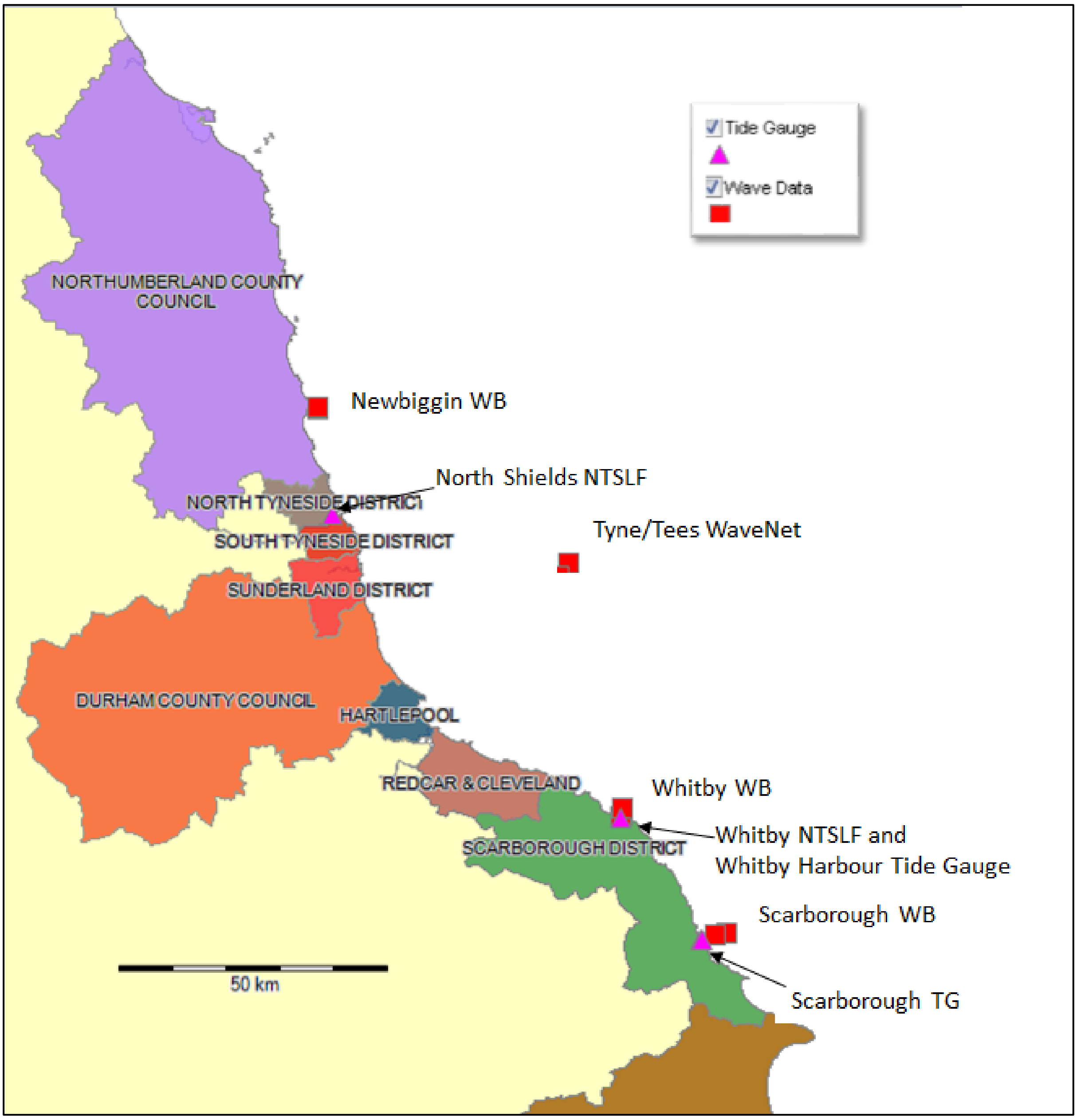


Figure 1.2 Updated data sets reviewed in this report

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 2015 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 2015 to March 2016 were compared to the previous data. Note that the analysis has included data available up to the end of March 2016 in order to cover the full winter 2015 to 2016 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 report (CH2M, 2015).

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 2015 to 2016 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)	31/03/2016 (ongoing)
North Shields NTSLF Tide Record	Tidal Levels	N/A	01/03/2015 (deployed 24/01/1946)	31/03/2016 (ongoing)
Tyne Tees WaveNet Site (WMO ID 62293)	Wave Data	65m	01/04/2015 (deployed 07/12/2006)	31/03/2016 (ongoing)
Whitby WB	Wave Data	17m	01/04/2015 (deployed 17/01/2013	31/03/2016 (ongoing)
Whitby Harbour TG	Tidal Levels	N/A	01/04/2015 (deployed 08/05/2013	31/12/2015 (ongoing)
Whitby NTSLF Tide Record	Tidal Levels	N/A	01/04/2015 (deployed 01/01/1991)	31/03/2015 (ongoing)
Scarborough WB2*	Wave Data	19m and 30m	01/04/2015 (deployed 17/01/2013)	31/03/2016 (ongoing)
Scarborough TG	Tidal Levels	N/A	01/01/2015 (deployed 28/04/2003)	31/12/2015 (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 2015-2016 are presented in Appendix B. There is a short gap in the data of about four days during January 2016 whilst the wave buoy was off station following an incident.

The new data set for 2015-2016 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 below. 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 previously measured wave heights were in the 2010/11 data. The wave heights over 5m in the latest data are from the late December to early January storm. There were no exceptionally long period waves in the latest data and longer period waves were observed in the 2010/11 and 2014/15 data sets.

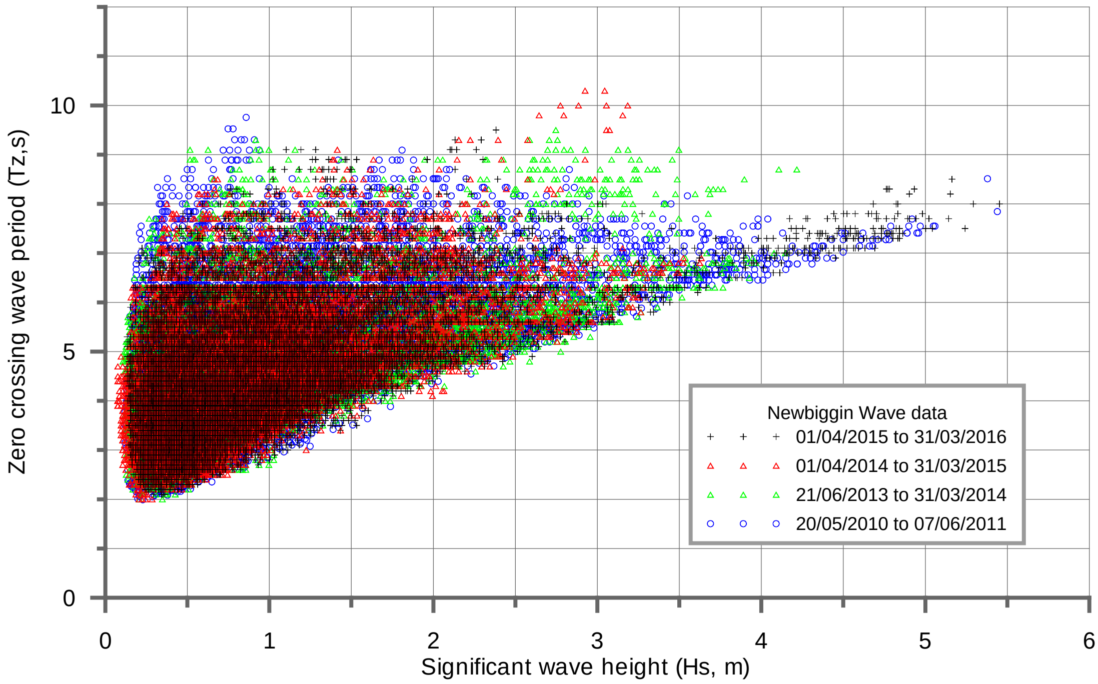


Figure 2.1 Scatter plot of Wave Height Vs Peak Period at Newbiggin wave buoy

2.1.2. Wave Rose

Wave roses showing wave height distribution by direction are shown in Figure 2.2 below. 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; (see right hand upper and both lower images). 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 or at least ten years would be required to assess how representative the four 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 5.1) indicates that the Newbiggin Ness site is relatively sheltered from waves from the north.

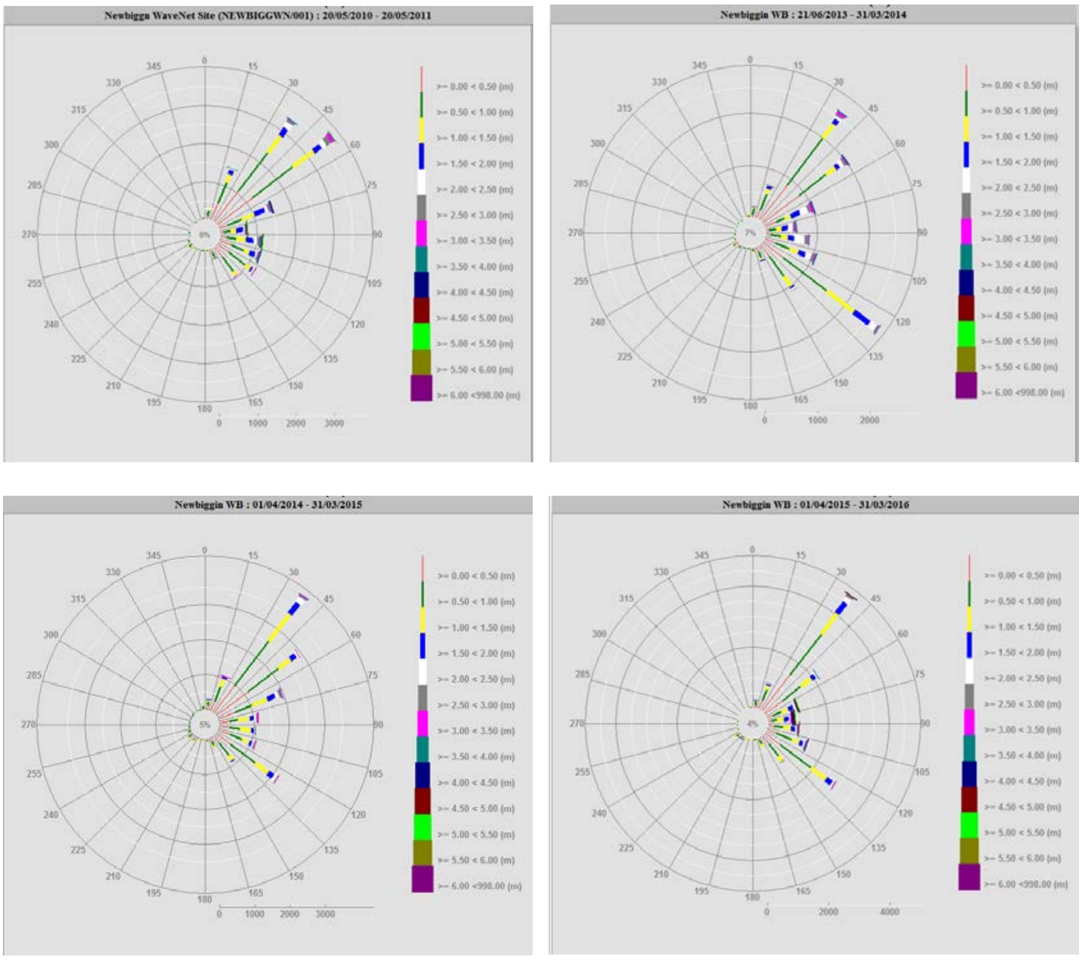


Figure 2.2 Wave roses for Newbiggin WB original deployment in 2010/11 and new data for 2013/14, 2014/15 and 2015/16

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. Note that the analysis for the other Cell 1 wave buoys use higher thresholds of 4m due to their more exposed locations. 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.

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

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

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 2015 to March 2016 was downloaded and imported into SANDS for analysis alongside the other monitoring data. An updated plot showing data availability for the NTSLF tidal gauge record at North Shields is shown in Figure 2.3 below (Data Source: BODC, https://www.bodc.ac.uk/data/online_delivery/). The data are at hourly intervals prior to 1993 and then at 15 minute intervals. The data were adjusted from Chart Datum to Ordnance Datum during import to SANDS. A more detailed plot of the data for 2015/16 is shown in Figure 2.4, showing that there were some significant gaps in the data, e.g. from 26/04/15 to 02/05/15 and 9/10/15 to 29/10/15 where the BODC QC had flagged the data as 'improbable'. There were also large gaps or suspect records in the data from 04/01/16 to 13/01/16.

Although there is occasional data available from 1946, there are many large gaps in the record up until 1964, (Figure 2.3), 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.

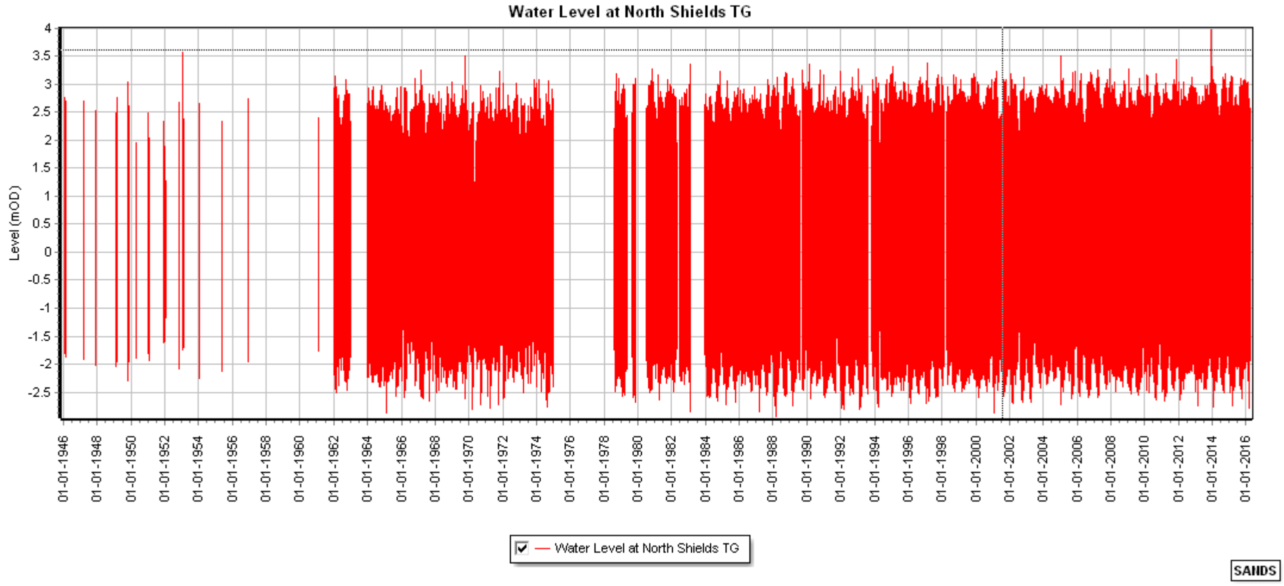


Figure 2.3 Plot of water level data availability at North Shields NTSLF Tide Gauge

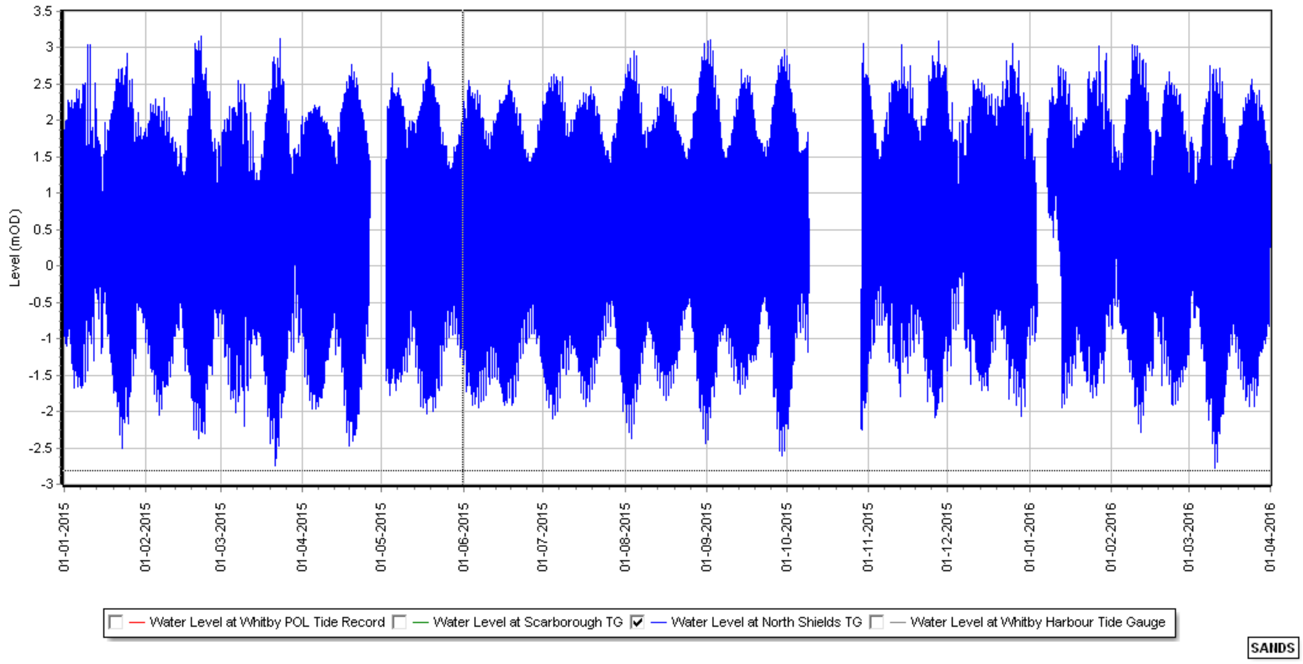


Figure 2.4 Plot of water level data availability for 2015/16 at North Shields NTSLF Tide Gauge

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/

Extreme water level predictions from the Environment Agency's (EA) 2011 national Coastal Flood Boundary (CFB) Conditions study for a location offshore from North Shields are shown in Table 2-5 below. This indicates that the December 5th 2013 storm surge, which caused extensive damage to defences and beaches on the east coast, had an annual exceedance probability (chance each year) of between 1 in 200 and 1 in 500 based on the analysis of previous data.

The full set of water level data from the North Shields tide gauge up to the end of March 2016 have been analysed in SANDS to derive extreme levels to compare to the EA 2011 CFB data. The Peak over Threshold approach was used with a threshold of 2.5m and data bins of 0.1m. The results, which had a good correlation coefficient of 0.979 for the Gumbel fit, are given in the right hand column of Table 2-5 and are around 5 to 10cm higher than the results of the EA 2011 CFB study. Note that the confidence levels for the EA data should also be assumed to apply to the local data analysis undertaken with SANDS. The set of return periods derived in SANDS is different to the EA 2011 CFB study so results are not available to compare for all return periods

Table 2-5 Predicted extreme tide levels at North Shields

Annual Exceedance probability	Extreme Level (m OD) from EA CFB Study (2011)[1]	Confidence intervals (m) from EA CFB Study (2011)[1]	Extreme levels from SANDS analysis of North Shields NTSLF(mOD)[2]
1 in 1	3.20	0.1	3.24
1 in 2	3.27	0.1	3.33
1 in 5	3.38	0.1	3.45
1 in 10	3.46	0.1	3.55
1 in 20	3.55	0.1	3.64
1 in 25	3.58	0.1	
1 in 50	3.67	0.1	3.76
1 in 75	3.72	0.1	
1 in 100	3.76	0.2	3.85
1 in 150	3.82	0.2	
1 in 200	3.87	0.2	3.95
1 in 250	3.90	0.2	
1 in 300	3.92	0.2	4.00
1 in 500	4.00	0.3	4.07
1 in 1,000	4.11	0.3	

Notes:
(1) data from EA (2011), Chainage 3630
http://evidence.environment-agency.gov.uk/FCERM/en/Default/FCRM/Project.aspx?ProjectID=F162D56F-87C4-4F14-B77B-A8A3EFDB363F&PageId=a0fe6dfc-506a-452c-9bff-a7ec06b4e6b0
(2) Data to end of March 2016, i.e. including the effects of the December 2013 surge.

According to data from the NTSLF, the highest predicted tide at North Shields (not allowing for atmospheric effects i.e. surge) for the period 2008 to 2026 is 3.13 mOD (5.73 mCD) that occurred on 30 September 2015, see Table 2-3. This high water level prediction is because there is a long period 18.6 year fluctuation in the influence of the Moon on our tides, and the peak of the current cycle occurred in September 2015. However, the actual recorded high water on 30 September 2015 was 2.94 mOD as there was a small negative surge at the time. As demonstrated by the data in Table 2-4 and Table 2-5, it is the combined influence of weather and tides that result in extreme water levels at the Cell 1 coast.

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 August 2015 to March 2016 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 (20/01/2007 to 13/02/07 and 21/01/2008 to 08/04/2009) that were filled by telemetry data. Future updates to this report should update this analysis as more accurate data becomes available. As previous reports have relied on more telemetry data this analysis supersedes that presented in the earlier reports for the Cell 1 programme.

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 2.5 showing a comparison of predicted and measured storms in November and December 2009 has been included from the previous report to demonstrate the issue.

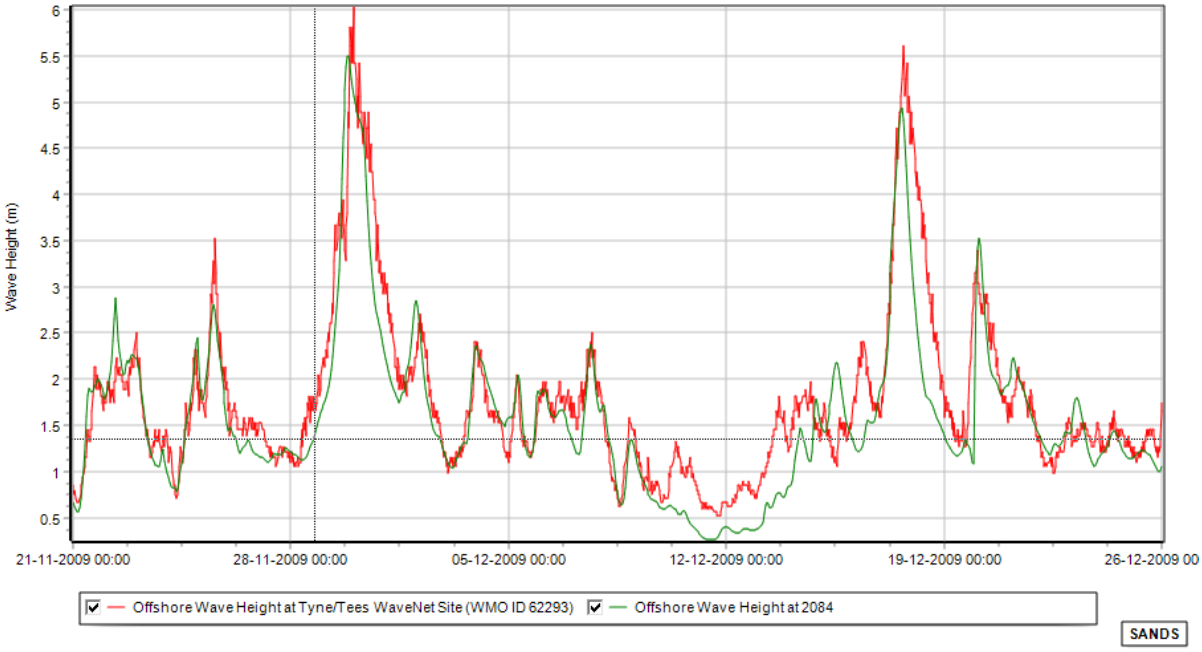


Figure 2.5 Comparison of recorded and modelled wave heights at Tyne Tees in winter 2009 showing under-prediction of modelled data

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 2016. The scatter table and wave rose was produced for the buoy now uses nine 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 2015-16 is shown in Figure 2.6 below. This shows that generally the four wave buoys record similar storms and although highest storm wave heights are often observed at Tyne /Tees this is not always the case; sometimes wave heights are larger at Scarborough as the distribution observed varies with each storm. The largest storm in the period January 2015 to March 2016 was in early January 2016. However, there was a short duration storm in November, which had a larger waves with largest Hs of 7.1m.

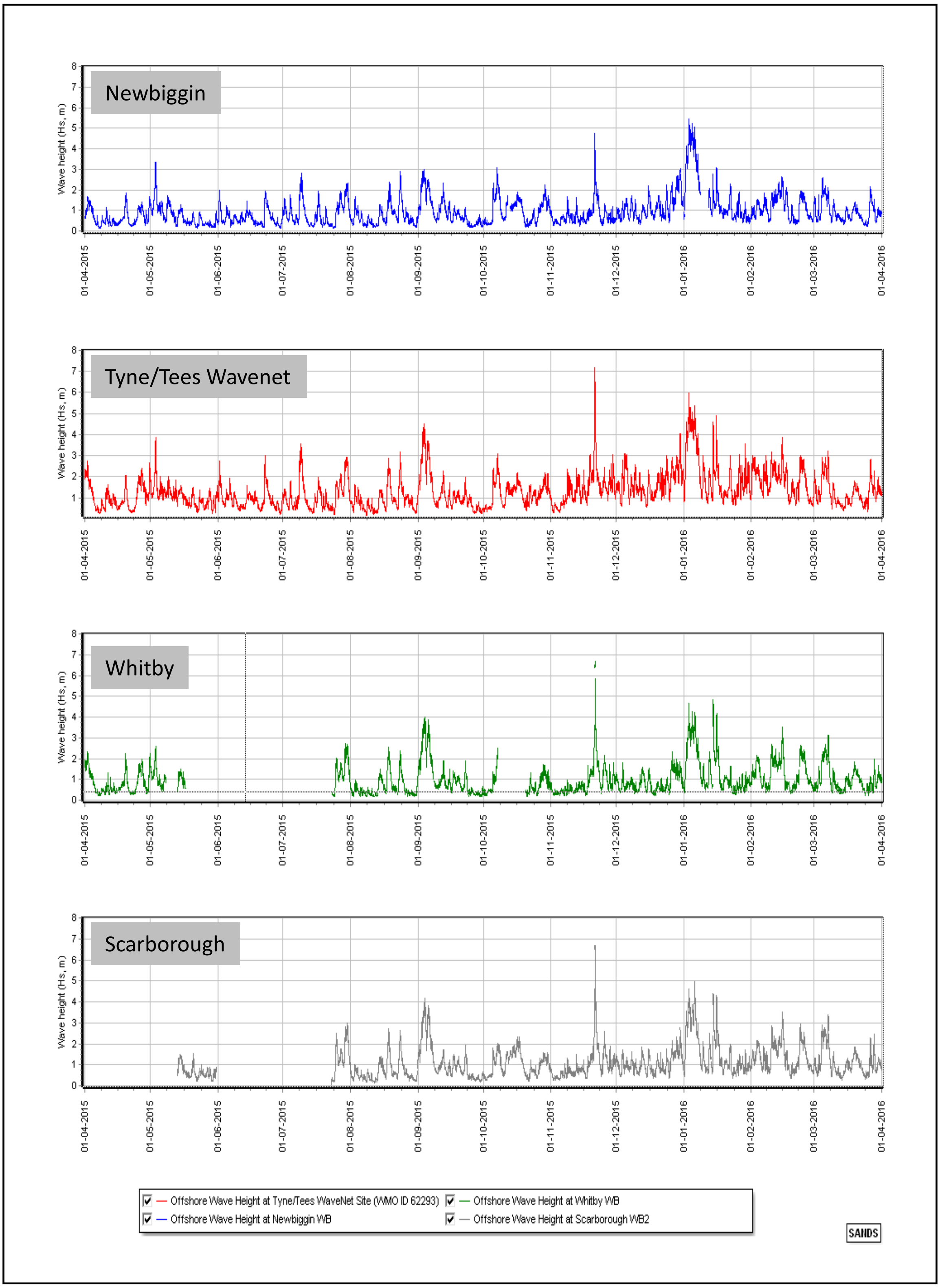


Figure 2.6 Comparison of recorded wave heights at Tyne Tees to the Cell 1 programme buoys from April 2015 to March 2016

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 2.7. 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.

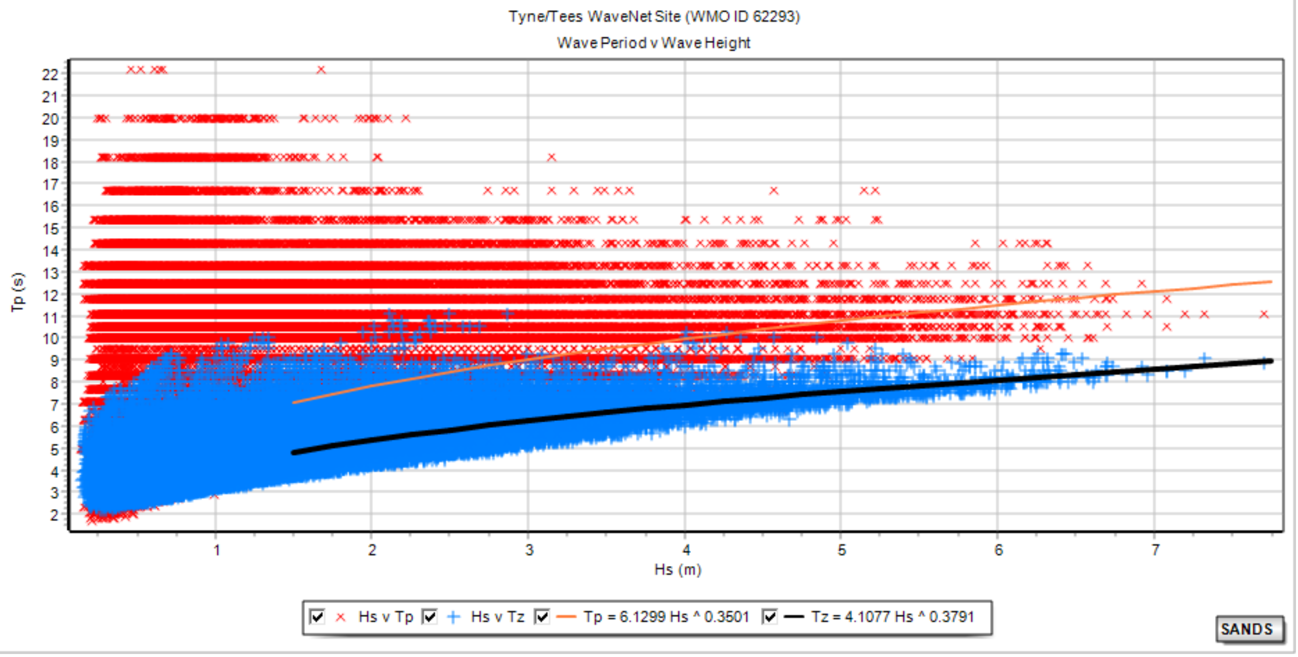


Figure 2.7 Scatter plot of Wave Height Vs Peak Period at Tyne Tees wave buoy site

2.3.2. Wave Rose and Wave Direction Scatter Tables

The wave rose for Tyne Tees in Figure 2.8 has been updated to include nine 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.

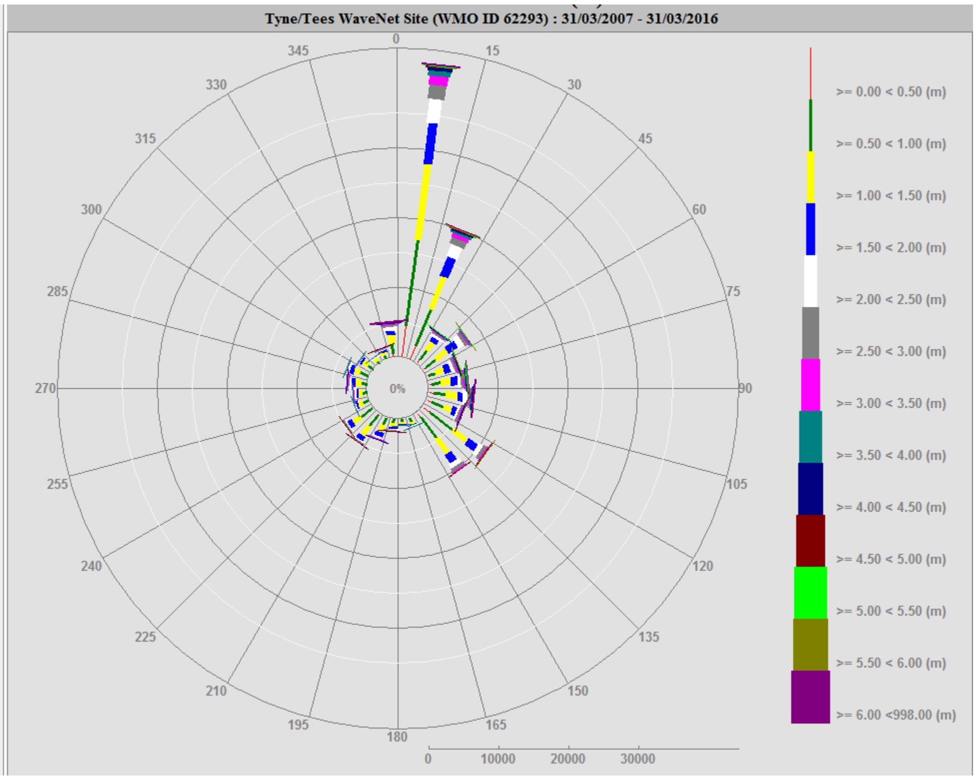


Figure 2.8 Wave Rose at Tyne Tees wave buoy site (WMO ID 62293)

The associated wave height and wave period vs wave direction data are provided below in Table 2-6 and Table 2-7 respectively.

Table 2-6 Wave Height and Direction Scatter Table for Tyne Tees WaveNet Site

Offshore Wave Height	Offshore Wave Direction												
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	270-300	300-330	330-360	Total
0-0.5	6759	1273	687	1505	2096	303	251	673	229	232	207	747	14962
0.5-1	17998	3520	2405	3626	8011	888	1727	4075	1570	1999	1210	2035	49064
1-1.5	15950	3421	2761	2953	5222	658	1538	2981	1252	1913	1261	1651	41561
1.5-2	8929	2434	1958	1470	2924	321	940	1425	659	1173	510	999	23742
2-2.5	5222	1275	948	911	1599	146	440	388	272	622	198	619	12640
2.5-3	2879	601	594	586	826	48	148	221	165	293	87	406	6854
3-3.5	1941	339	407	315	355	12	34	52	50	64	16	177	3762
3.5-4	1033	183	243	166	163	5	12	13	6	12	3	93	1932
4-4.5	571	73	224	125	86		4	2		1		62	1148
4.5-5	350	35	168	79	22		1	4				41	700
5-5.5	178	23	93	60								30	384
5.5-6	96	2	37	29	1							20	185
6-6.5	61		8	20								8	97
6.5-7	17		5	3								2	27
7-7.5	3		1									2	6
7.5-8	10												10
Total	61997	13179	10539	11848	21305	2381	5095	9834	4203	6309	3492	6892	

Location: Tyne/Tees WaveNet Site (WMO ID62293);
Date range: 01/04/2007 to 31/03/2016 (9 years of data)
Offshore Wave Direction Peak (x) vs Offshore Wave Height Hm0 (y), showing numbers of 30 min observations.

Table 2-7 Wave Period and Direction Scatter Table for Tyne Tees WaveNet Site

Offshore Wave Direction

Offshore Wave Tp	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	270-300	300-330	330-360	Total
0-2	1	1	1	1	2	3		3				1	13
2-4	504	191	158	417	1837	881	1541	4023	1773	1875	973	409	14582
4-6	3751	2394	2703	5123	11644	1294	3265	5380	2193	4024	2343	2530	46644
6-8	10521	5674	4784	4797	6229	147	214	326	203	347	141	1676	35059
8-10	14146	3252	1992	1209	1462	27	19	35	14	14	6	555	22731
10-12	22775	1484	887	282	80	12	15	29	12	30	16	1172	26794
12-14	6727	141	10	2	23	10	26	25	4	10	1	312	7291
14-16	2609	23	4	3	16	7	8	9		4	3	157	2843
16-18	540	9		11	10		6	4	4	4	2	44	634
18-20	317	8		3	2		1			1	7	25	364
20-22	102	2										11	115
22-24	4												4
Total	61997	13179	10539	11848	21305	2381	5095	9834	4203	6309	3492	6892	

Location: Tyne/Tees WaveNet Site (WMO ID62293);
Date range: 01/04/2007 to 31/03/2016 (9 years of data
Offshore Wave Direction Peak (x) vs Offshore Peak Wave Period Tp (y), showing numbers of 30 minute observations.

2.3.3. Extremes Analysis

The extreme wave height analysis undertaken for the Tyne Tees buoy location in the baseline report has been updated. As before, a wave height threshold of 4.6m was used, which provided 60 peaks in 9.3 years. The maximum significant wave height recorded over the period was 7.92m on 23/03/2008. The Gumbel distribution used for extrapolation gives a good correlation coefficient of 0.992 and the visual fit appeared satisfactory. The results are generally 0.2 to 0.3m higher than given in last year's report and it is noted that the new data includes three new peaks in the top 20 wave heights (7.2m on 21/11/2015, 6.7m on 01/02/2015 and 6.0m on 03/01/2016). Given the length of the record, the extremes data should not be considered reliable beyond a 1 in 30 year return period. The results of the extremes analysis are shown in Table 2-8 below.

Table 2-8 Extremes Analysis for Tyne Tees buoy

Return Period (1 in X years)	Gumbel Fit Extreme Wave Height (Hs, m)
0.2	4.9
0.3	5.5
0.5	5.9
1	6.5
2	7.0
3	7.3
5	7.7
10	8.2
20	8.7
30	9.0

2.3.4. 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 31/03/2016. Note that the data available from August 2015 to March 2016 is the telemetry data download, as the checked post-recovery data is not yet available for this period and only telemetry data is available for 20/01/2007 to 13/02/07 and 21/01/2008 to 08/04/2009. Future updates to this report should update this analysis as more accurate data becomes available. As noted above, the analyses reported in previous reports has been updated by repeating the storms analysis with the quality controlled post-recovery data.

The storm analysis results are presented in Table 2-9 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.

Plots of storm direction and storm duration are shown in Figure 2.9 and Figure 2.10 below. 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. In 2015-15 none of the four storms had wave directions from south east.

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 2-9 for this report shows there were only four storms in 2015, with one at the end of January / early February one in September and October and the last starting at the end of December, although the peak was on 3rd January 2016. None of these storms appear particularly atypical from the overall record, although the storm at the end of the year was the third longest in the record.

Table 2-9 Storm Analysis at Tyne Tees WaveNet Buoy (data to 31st March 2016)

General Storm Information							At Peak					
StartTime	EndTime	Dur (hr)	Peak of Storm[1]	Mean Dir (º)	No of Events	Mean Direction Vector (º)	Hs (m)	Tp (s)	Tz (s)	Dir (º)	Energy @ Peak (KJ/m/s)	Total Energy (KJ/m)
19/03/2007 10:30	21/03/2007 05:30	43.0	20/03/07 15:30	32	81	79.16	6.3	14.3	8.3	20	1.6 E+4	1.8 E+7
25/06/2007 20:00	27/06/2007 00:00	28.0	26/06/07 10:00	66	35	80.12	4.6	10.0	7.1	20	4.2 E+3	3.5 E+6
26/09/2007 03:00	27/09/2007 07:00	28.0	26/09/07 19:00	24	42	79.19	4.5	11.8	7.7	8	5.5 E+3	4.8 E+6
08/11/2007 20:00	**12/11/2007 15:30**	**91.5**	**09/11/07 11:30**	**22**	**68**	**79.19**	**6.3**	**14.3**	**8.9**	**8**	**1.6 E+4**	**1.8 E+7**
19/11/2007 04:00	26/11/2007 00:00	164.0	23/11/07 07:00	100	68	80.89	4.8	11.8	8.2	4	6.3 E+3	9.3 E+6
08/12/2007 03:00	10/12/2007 14:30	59.5	08/12/07 03:30	86	13	84.14	4.2	12.5	7.7	18	5.3 E+3	1.5 E+6
03/01/2008 10:30	04/01/2008 08:00	21.5	03/01/08 16:00	78	29	13.77	4.8	10.0	7.4	72	4.6 E+3	3.2 E+6

General Storm Information							At Peak					
StartTime	EndTime	Dur (hr)	Peak of Storm[1]	Mean Dir (º)	No of Events	Mean Direction Vector (º)	Hs (m)	Tp (s)	Tz (s)	Dir (º)	Energy @ Peak (KJ/m/s)	Total Energy (KJ/m)
16/01/2008 11:30	16/01/2008 14:30	3.0	16/01/08 11:30	8	2	81.52	4.1	10.5	7.5	7	3.6 E+3	2.2 E+5
01/02/2008 15:00	02/02/2008 09:30	18.5	02/02/08 00:00	33	37	80.57	6.0	16.4	9.0	17	1.9 E+4	1.1 E+7
10/03/2008 08:30	10/03/2008 12:30	4.0	10/03/08 11:00	146	9	307.51	4.6	9.6	6.5	141	3.8 E+3	7.3 E+5
17/03/2008 15:00	**25/03/2008 03:00**	**180.0**	**22/03/08 05:00**	**62**	**79**	**83.92**	**7.9**	**14.8**	**9.0**	**6**	**2.7 E+4**	**2.3 E+7**
05/04/2008 22:00	07/04/2008 05:00	31.0	06/04/08 19:00	39	25	83.47	4.6	13.9	7.6	6	7.9 E+3	3.9 E+6
20/07/2008 16:00	21/07/2008 09:30	17.5	20/07/08 23:30	15	8	76.00	4.2	11.8	7.6	11	4.9 E+3	9.1 E+5
03/10/2008 03:00	03/10/2008 20:30	17.5	03/10/08 16:30	29	33	82.27	4.7	13.6	7.6	23	8.1 E+3	5.4 E+6
21/11/2008 04:00	25/11/2008 12:30	104.5	22/11/08 11:30	14	122	76.00	6.0	15.6	8.5	11	1.7 E+4	2.6 E+7
10/12/2008 12:00	13/12/2008 18:00	78.0	13/12/08 08:00	109	37	332.05	4.9	10.0	7.2	129	4.7 E+3	4.0 E+6
31/01/2009 16:30	03/02/2009 09:00	64.5	02/02/09 22:00	84	58	7.11	5.8	11.4	8.5	84	8.7 E+3	8.2 E+6
23/03/2009 20:30	28/03/2009 20:30	120.0	28/03/09 18:30	92	26	89.64	4.9	11.0	7.6	0	5.7 E+3	3.2 E+6
10/07/2009 01:30	10/07/2009 02:30	1.0	10/07/09 01:30	12	3	78.54	4.4	11.8	7.4	10	5.3 E+3	3.5 E+5
29/11/2009 20:00	**30/11/2009 16:30**	**20.5**	**30/11/09 00:30**	**18**	**42**	**72.35**	**6.2**	**11.1**	**7.8**	**14**	**9.4 E+3**	**6.7 E+6**
17/12/2009 10:30	18/12/2009 06:30	20.0	17/12/09 17:00	62	41	28.25	5.8	11.1	8.0	68	8.1 E+3	6.3 E+6
30/12/2009 09:00	30/12/2009 23:00	14.0	30/12/09 12:30	84	26	7.56	5.1	9.1	7.1	89	4.2 E+3	2.4 E+6
06/01/2010 05:30	06/01/2010 11:00	5.5	06/01/10 06:30	32	11	58.33	4.3	12.5	7.1	11	5.6 E+3	1.4 E+6
29/01/2010 10:30	30/01/2010 00:30	14.0	29/01/10 22:30	23	29	83.44	5.6	10.0	7.8	6	6.2 E+3	3.1 E+6
26/02/2010 22:30	27/02/2010 03:00	4.5	27/02/10 01:00	17	9	74.02	4.9	10.0	7.8	18	4.8 E+3	9.7 E+5
31/03/2010 16:30	31/03/2010 17:30	1.0	31/03/10 17:00	243	3	90.72	4.1	10.5	6.8	356	3.6 E+3	3.1 E+5
19/06/2010 07:00	20/06/2010 10:00	27.0	19/06/10 22:30	21	51	69.69	5.2	13.3	8.0	25	9.4 E+3	9.0 E+6
29/08/2010 13:30	30/08/2010 06:30	17.0	30/08/10 01:00	219	29	91.94	4.8	10.5	7.5	6	5.0 E+3	3.1 E+6
06/09/2010 22:30	07/09/2010 16:30	18.0	07/09/10 15:30	99	28	353.93	4.7	10.5	8.3	90	4.7 E+3	2.9 E+6
17/09/2010 07:00	17/09/2010 23:00	16.0	17/09/10 10:30	10	23	80.54	4.7	13.3	8.0	14	7.6 E+3	3.9 E+6
24/09/2010 03:00	26/09/2010 03:30	48.5	24/09/10 08:00	19	91	72.92	5.2	11.8	7.7	3	7.4 E+3	1.4 E+7
19/10/2010 23:30	24/10/2010 17:30	114.0	20/10/10 10:00	13	26	77.22	4.3	13.3	7.3	17	6.4 E+3	3.0 E+6
08/11/2010 14:00	**09/11/2010 20:30**	**30.5**	**09/11/10 10:00**	**88**	**60**	**2.56**	**5.9**	**11.1**	**8.0**	**66**	**8.3 E+3**	**8.0 E+6**
17/11/2010 12:00	17/11/2010 18:30	6.5	17/11/10 12:00	133	9	322.03	4.7	9.1	6.9	132	3.6 E+3	7.0 E+5
28/11/2010 21:00	02/12/2010 10:00	85.0	29/11/10 21:00	81	57	10.62	5.2	11.1	7.7	58	6.5 E+3	7.0 E+6
09/12/2010 06:30	09/12/2010 08:30	2.0	09/12/10 08:30	13	2	78.54	4.1	10.0	7.3	10	3.4 E+3	1.8 E+5
16/12/2010 13:30	17/12/2010 10:30	21.0	17/12/10 03:30	21	34	80.64	4.6	12.5	7.5	14	6.5 E+3	4.0 E+6
23/07/2011 09:30	**24/07/2011 12:00**	**26.5**	**24/07/11 01:00**	**23**	**46**	**67.61**	**4.9**	**11.8**	**7.7**	**24**	**6.7 E+3**	**6.5 E+6**
24/10/2011 18:30	25/10/2011 16:00	21.5	25/10/11 01:00	102	30	349.39	4.8	10.0	7.8	103	4.6 E+3	3.1 E+6
09/12/2011 08:30	09/12/2011 12:00	3.5	09/12/11 10:30	6	6	83.80	4.5	14.3	8.3	6	8.0 E+3	1.2 E+6
05/01/2012 15:30	06/01/2012 05:00	13.5	06/01/12 00:30	29	24	81.41	4.5	11.8	7.3	14	5.5 E+3	3.0 E+6

General Storm Information							At Peak					
StartTime	EndTime	Dur (hr)	Peak of Storm[1]	Mean Dir (º)	No of Events	Mean Direction Vector (º)	Hs (m)	Tp (s)	Tz (s)	Dir (º)	Energy @ Peak (KJ/m/s)	Total Energy (KJ/m)
03/04/2012 13:30	04/04/2012 10:30	21.0	04/04/12 03:00	64	43	26.54	5.7	10.0	7.5	90	6.4 E+3	5.6 E+6
24/09/2012 07:30	25/09/2012 11:00	27.5	24/09/12 17:30	73	54	17.19	5.3	11.1	7.7	77	6.8 E+3	8.0 E+6
26/10/2012 12:00	27/10/2012 15:00	27.0	26/10/12 23:00	11	44	78.92	4.9	15.4	7.5	11	1.1 E+4	7.2 E+6
05/12/2012 15:00	**15/12/2012 01:30**	**226.5**	**14/12/12 18:30**	**82**	**50**	**40.86**	**6.1**	**10.0**	**7.7**	**107**	**7.2 E+3**	**6.2 E+6**
20/12/2012 06:00	21/12/2012 14:30	32.5	20/12/12 23:30	103	63	347.32	6.0	10.5	8.0	103	7.7 E+3	9.1 E+6
18/01/2013 17:30	22/01/2013 07:30	86.0	21/01/13 09:30	83	62	7.62	6.8	11.1	8.3	83	1.1 E+4	1.2 E+7
06/02/2013 08:00	07/02/2013 08:30	24.5	06/02/13 12:30	56	47	82.60	5.6	11.8	7.7	11	8.6 E+3	7.1 E+6
07/03/2013 21:00	11/03/2013 04:00	79.0	08/03/13 04:00	67	53	24.26	5.1	10.0	7.7	82	5.2 E+3	5.8 E+6
18/03/2013 07:00	25/03/2013 02:00	163.0	23/03/13 10:30	86	166	4.46	7.3	11.1	9.1	89	1.3 E+4	3.0 E+7
23/05/2013 18:00	**24/05/2013 12:00**	**18.0**	**24/05/13 00:00**	**18**	**37**	**77.94**	**7.7**	**11.1**	**8.9**	**10**	**1.4 E+4**	**7.7 E+6**
10/09/2013 12:00	10/09/2013 21:00	9.0	10/09/13 18:00	12	16	77.96	4.8	10.0	7.0	13	4.5 E+3	1.8 E+6
09/10/2013 21:30	14/10/2013 01:00	99.5	10/10/13 19:00	79	68	78.55	6.1	11.8	8.2	24	1.0 E+4	1.3 E+7
29/11/2013 22:00	30/11/2013 08:00	10.0	30/11/13 00:00	52	19	85.24	6.1	11.8	8.2	10	1.0 E+4	3.5 E+6
05/12/2013 14:00	07/12/2013 04:30	38.5	06/12/13 19:30	27	70	80.86	5.2	16.7	9.5	8	1.5 E+4	1.5 E+7
27/12/2013 09:30	27/12/2013 12:30	3.0	27/12/13 10:00	216	3	250.13	4.2	7.1	6.6	203	1.8 E+3	1.3 E+5
19/01/2014 17:30	19/01/2014 18:30	1.0	19/01/14 17:30	70	2	20.75	4.4	10.5	8.9	65	4.3 E+3	2.2 E+5
05/02/2014 04:00	05/02/2014 19:00	15.0	05/02/14 07:00	141	11	317.05	4.6	9.1	7.3	131	3.4 E+3	8.9 E+5
12/02/2014 20:00	14/02/2014 19:30	47.5	12/02/14 20:30	178	13	269.88	4.3	9.1	6.3	139	3.0 E+3	8.8 E+5
21/10/2014 21:00	**22/10/2014 01:30**	**4.5**	**21/10/14 22:30**	**6**	**6**	**84.49**	**4.6**	**11.1**	**7.4**	**6**	**5.1 E+3**	**7.2 E+5**
17/11/2014 05:00	17/11/2014 09:00	4.0	17/11/14 05:00	54	2	43.42	4.2	11.1	7.4	42	4.2 E+3	2.0 E+5
31/01/2015 08:30	02/02/2015 03:30	43.0	31/01/15 23:00	132	75	88.71	6.2	12.5	8.0	7	1.2 E+4	1.4 E+7
03/09/2015 05:30	04/09/2015 06:00	24.5	03/09/15 18:30	13	15	78.05	4.4	10.5	6.8	11	4.2 E+3	1.6 E+6
21/11/2015 01:30	**21/11/2015 14:30**	**13.0**	**21/11/15 05:30**	**72**	**27**	**85.91**	**7.1**	**11.8**	**8.5**	**356**	**1.4 E+4**	**5.7 E+6**
30/12/2015 09:30	07/01/2016 12:00	194.5	03/01/16 13:00	81	190	10.27	5.3	11.8	8.5	75	7.6 E+3	2.5 E+7
14/01/2016 11:00	16/01/2016 03:00	40.0	15/01/16 23:30	58	19	80.78	4.7	12.5	7.8	27	6.9 E+3	2.1 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 $L_o = g.Tp^2/2.\pi$

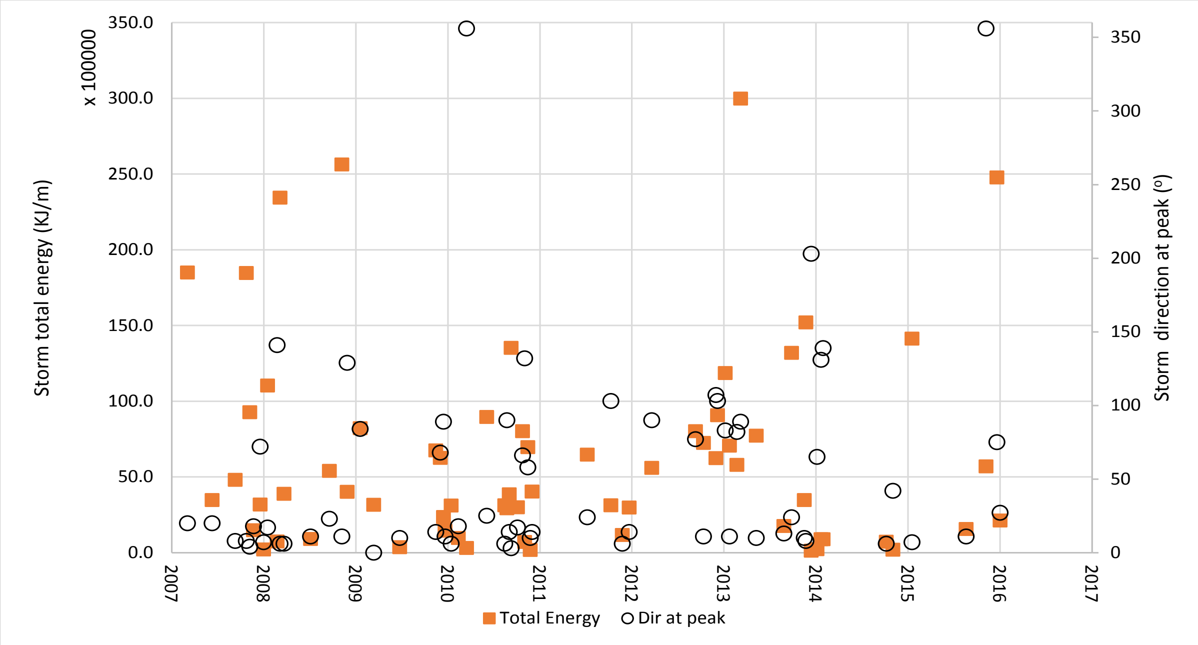


Figure 2.9 Total storm energy and wave direction at the peak of each storm for Tyne Tees Wave Buoy

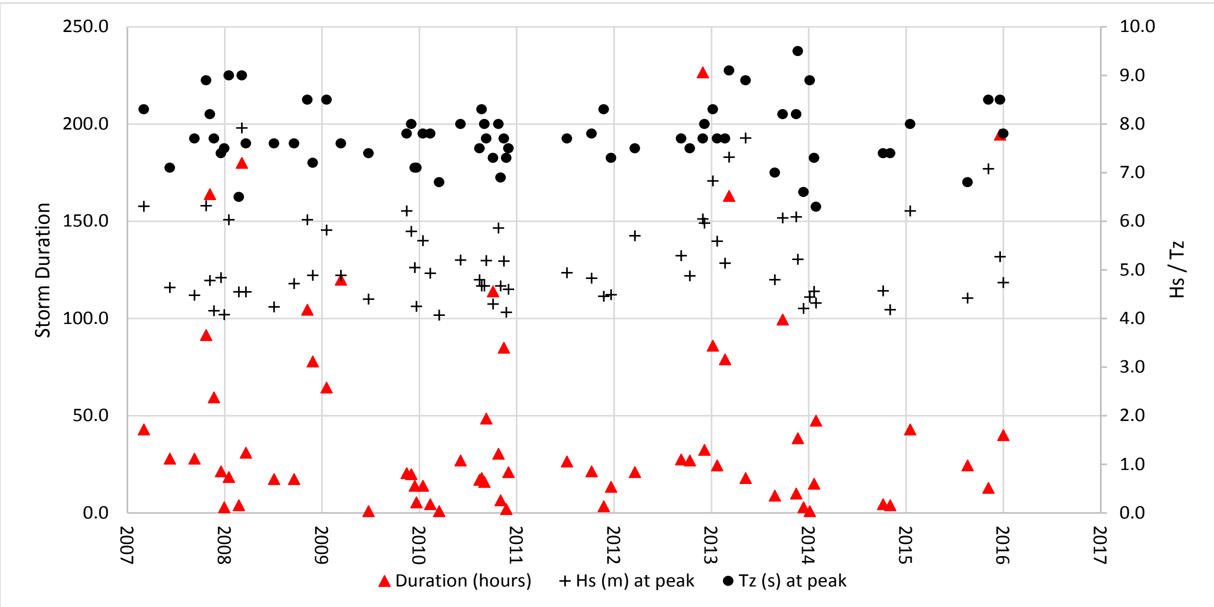


Figure 2.10 Storm duration, with Hs and Tz at peak for Tyne Tees Wave Buoy

A comparison between the wave energy at Tyne Tees Wave buoy, and wave energy from storms in the Met Office model hindcast is shown in Figure 2.11. Visual inspection of Figure 2.11 shows the model data indicates a decline in storm energy since a peak in 2004/05 up to the end of the dataset in 2012, however there were similar patterns from 1995 to 2002 and from 1981 to 1985, so this is not unusual. The data from the Tyne Tees buoy also shows a decline from 2009, but then shows an increase over the winter 2013/14 and another increase in 2015/16.

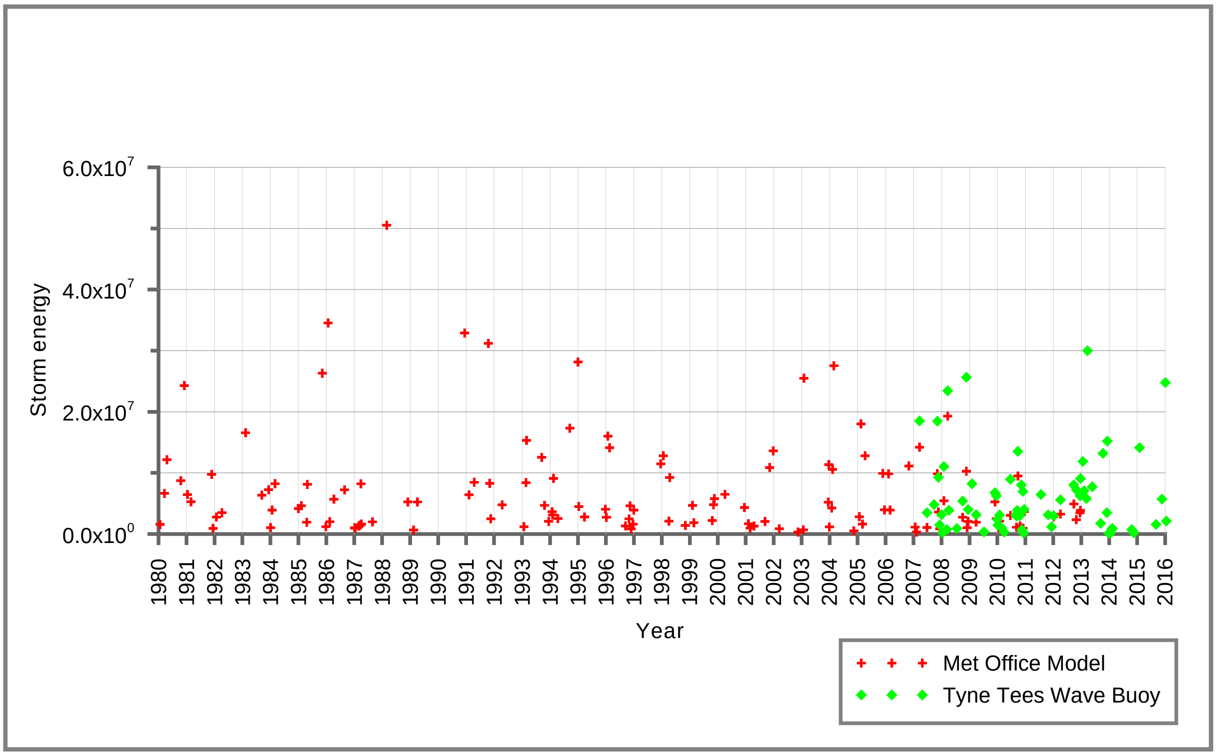


Figure 2.11 Storm energy comparison for Met Office model and Tyne Tees Wave Buoy

An analysis of the joint occurrence of waves and water levels has been undertaken using the measured NTSLF water level data from North Shields and the measured wave data from the Tyne Tees buoy. The results, which supersede those in the earlier reports, are presented as a scatter table of the number of occurrences of joint events in Table 2-10.

Table 2-10 Scatter table for Tyne Tees WaveNet data vs North Shields water levels

	Water level (mOD) at North Shields														
	-2.5 - -3.0	-2.0 - -2.5	-1.5 - -2.0	-1.0 - -1.5	-0.5 - -1.0	0.0 - -0.5	0.5 - 0.0	1.0 - 0.5	1.5 - 1.0	2.0 - 1.5	2.5 - 2.0	3.0 - 2.5	3.5 - 3.0	4.0 - 3.5	4.5 - 4.0
Wave Height (Hs,m) at Tyne/Tees															
7.00 - 8.00	0	0	0	0	3	2	0	1	2	2	6	0	0	0	0
6.00 - 7.00	0	0	3	13	12	15	12	27	22	12	9	10	0	0	0
5.00 - 6.00	0	0	7	35	71	78	65	63	79	82	56	28	3	0	0
4.00 - 5.00	2	16	52	185	235	217	195	207	209	234	151	37	5	1	0
3.00 - 4.00	5	51	198	590	796	706	628	640	720	747	478	110	3	3	0
2.00 - 3.00	12	153	827	2025	2631	2507	2161	2167	2643	2658	1597	448	21	0	0
1.00 - 2.00	14	544	3079	7024	8694	8012	6839	6892	8419	8700	5554	1356	50	0	0
0.00 - 1.00	21	725	3565	6898	8559	7501	6514	6608	8182	8594	5391	1495	40	0	0

Based on 8.98 years of data accounting for gaps with records at 0.5 hour intervals,
Data period is 7th December 2006 to 31 March 2016

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 2016. The data were imported into SANDS for comparison and analysis alongside the other available monitoring data; see Figure 2.6.

There are several significant gaps in the new Whitby data in 2015 while the buoy was off station due to damage. This includes 8th May to 13th May, 17th May to 23rd July and from 17th to 21st October. There are also small gaps in November 2015 and January 2016. 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 2.12 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.

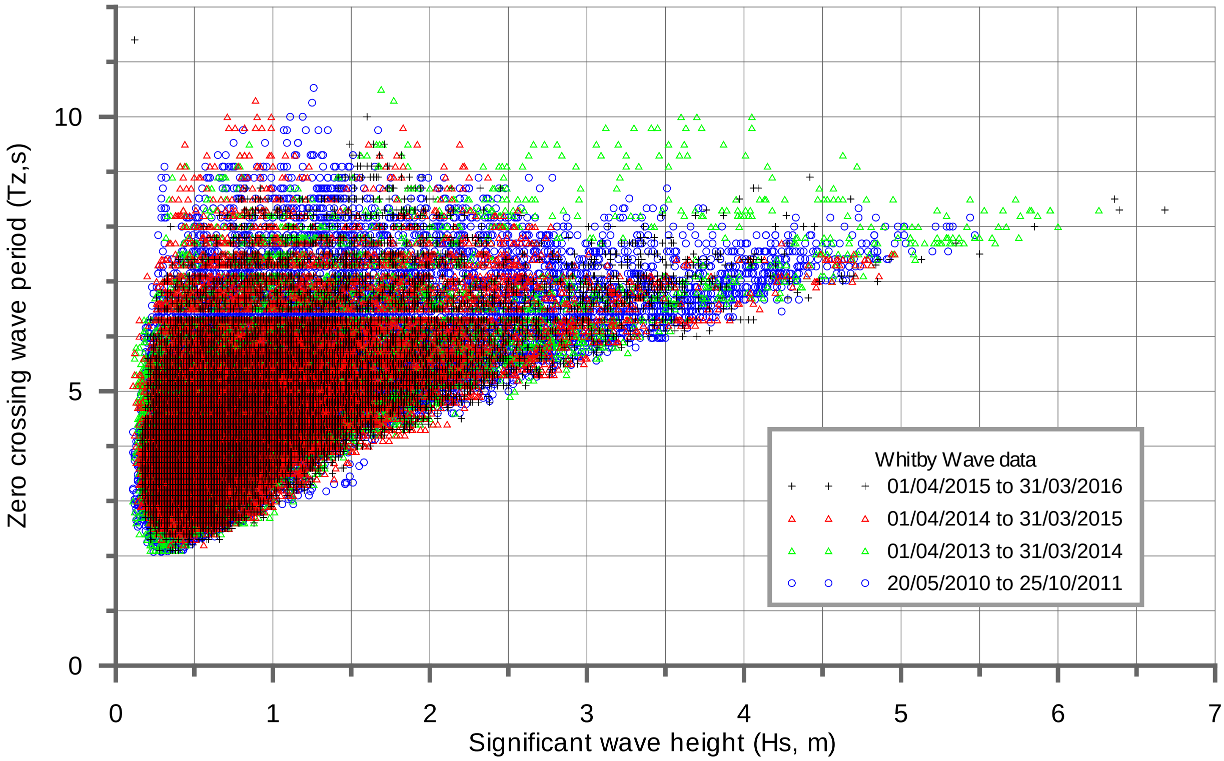


Figure 2.12 Scatter plot of Wave Height Vs Zero crossing period at Whitby wave buoy site

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 2.13 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).

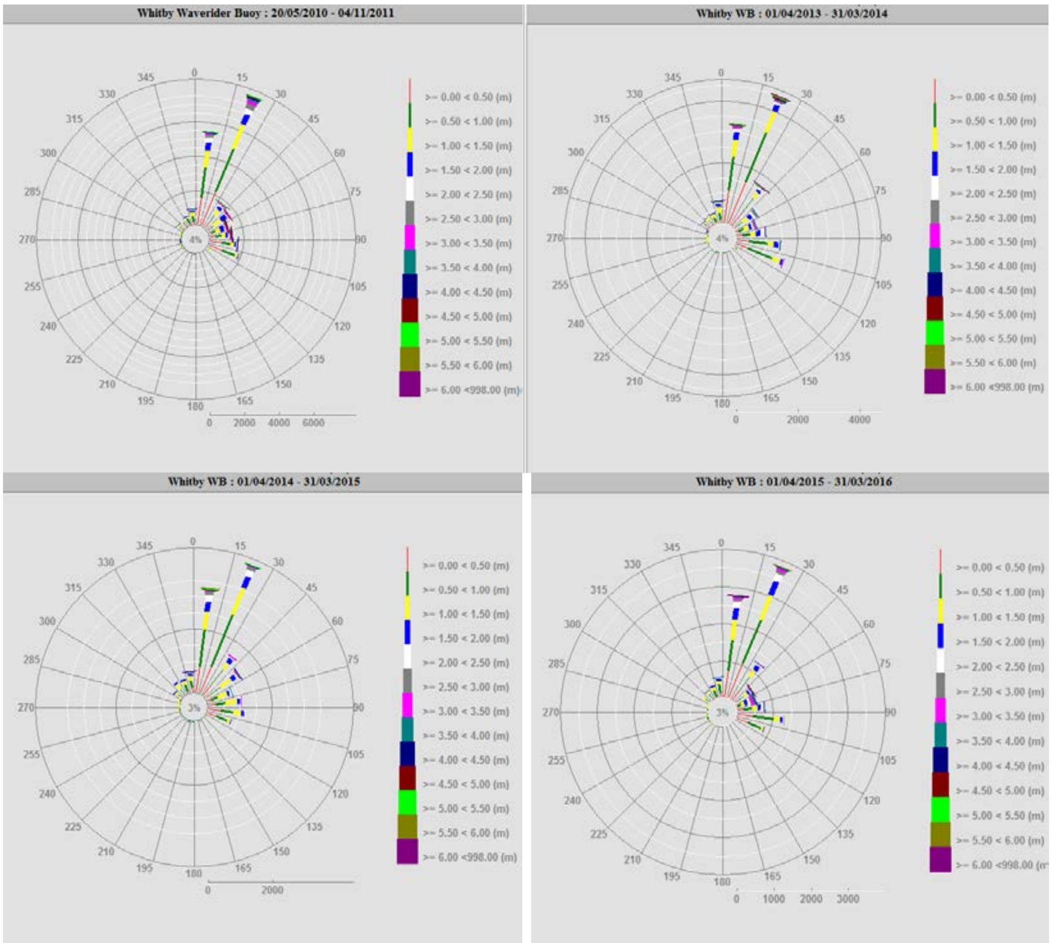


Figure 2.13 Wave Roses at Whitby wave buoy site

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 last year's report using a slightly lower threshold of 3.9m to detect more storms and the updated results with the latest data now to 31/03/2016 are presented in Table 2-11 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 25th September 2010. The storms analysis of the new data is shown in Table 2-12. 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 2-11 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

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)
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 2-11 and Table 2-12 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 2-12 Storm analysis for Whitby WB (data 17/01/2013 to 31/03/2016)

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

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 5.8m during the storm from 23rd to 24th May 2013. The new data for 2015/16 shows a new largest wave height of 6.7m Hs during the short storm on 21st November 2015 and this also had the highest wave energy at the peak of the storm.

As only four 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, see also Section 3.3.

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.

Table 2-13 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

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

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.

An example plot of water level data from the POL tidal gauge record at Whitby is shown in Figure 2.14 below (Source: BODC, https://www.bodc.ac.uk/data/online_delivery/). 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 2015 was added to the analysis in the 2014/15 report. Data for April 2015 to March 2016 have been added to the analysis for this report. All data were adjusted from Chart Datum to Ordnance datum when imported to SANDS.

There are occasional gaps in the Whitby data (Figure 2.14), but the overall record appears fairly consistent. However, there are missing data and / or the data may be invalid during extreme low waters since about 2011 (see Sections 3.4 and 4.1). In 2015 there are very large gaps in the quality controlled data with almost all data from April 2015 onwards flagged as suspect due to issues with the gauge (Figure 2.15). The NTSLF annual report for 2015[1] states that "Both channels are flagged from April onwards. The site suffers from siltation and in the past the pressure points have become buried due to siltation at the site". The report also indicates that the site was visited by NTSFL on 28/04/2015 for a survey following harbour works in the vicinity of the tide gauge and again on 29/10/2015 for maintenance and a compressor change.

The spike in the high water levels shown near the end of the plot in Figure 2.14 is the storm surge level of 4.32 mOD at 17:15 on the 5th December 2013. This shows how exceptional the conditions of that event were, with the previous maximum observed water level of 3.6 mOD occurring at 18:00 on 1st February 1983 (note that prior to 1990 only hourly data are available and so the maximum water level may have been higher than the recorded 3.6 mOD). The 15 highest water levels observed at Whitby are presented in descending order in Table 2-14. The maximum water level recorded in 2015 was 3.34mOD, which is the 18th highest.

Table 2-14 Maximum observed water levels at Whitby NTSLF gauge

Date	Level (mOD)
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
11/09/2010 05:30	3.35

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

Extreme water level predictions from the Environment Agency (EA)'s 2011 national Coastal Flood Boundary (CFB) Conditions study for a location offshore from Whitby are shown in Table 2-15 below. This indicates that based on preceding conditions the December 5th 2013 storm surge, which caused extensive flooding around Whitby town centre, had an annual exceedance probability (chance each year) of between 1 in 100 and 1 in 500.

In the previous annual reports, the water level data from the Whitby NTSLF tide gauge were also analysed in SANDS to derive extreme levels to compare to the EA 2011 CFB data. The

[1] UK Coastal Monitoring and Forecasting: Annual Report for 2015 for the UK National Tide Gauge Network, https://www.bodc.ac.uk/data/online_delivery/ntslf/reports/

analysis has been repeated with the latest data full data set. As in past reports, the Peak over Threshold approach was used, with a threshold of 2.2m and data bins of 0.1m. This analysis includes the 5th December 2013 storm. The results, which had a correlation coefficient of 0.972 for the Gumbel fit, are given in the right hand column of Table 2 15 are similar to those of the EA CFB study at low return periods but higher by about 0.1m for 1 in 5, increasing to 0.3m for 1 in 200. Note that the confidence levels for the EA data should also be assumed to apply to the local data analysis undertaken with SANDS. This increase in levels is due to the December 2013 surge, as previous analyses that excluded the December 2013 data show a good match with the CFB data. Note that the set of return periods derived in SANDS is different to the EA CFB study so results are not available to compare for all return periods.

Table 2-15 Predicted extreme tide levels at Whitby

Annual Exceedence probability	Extreme Level (m OD) from EA CFB Study (2011)[1]	Confidence intervals (m) from EA CFB Study (2011)[1]	Extreme levels from SANDS analysis of Whitby NTSLF (mOD)[2]
1 in 1	3.37	0.1	3.4
1 in 2	3.46	0.1	3.5
1 in 5	3.58	0.1	3.7
1 in 10	3.68	0.1	3.8
1 in 20	3.78	0.1	4.0
1 in 25	3.81	0.2	
1 in 50	3.92	0.2	4.1
1 in 75	3.98	0.2	
1 in 100	4.02	0.3	4.3
1 in 150	4.09	0.3	
1 in 200	4.14	0.3	4.4
1 in 250	4.17	0.3	
1 in 300	4.20	0.4	
1 in 500	4.29	0.4	
1 in 1,000	4.41	0.5	

Note: (1) data from EA (2011), Chainage 3718
(2) Uses all available data to end of March 2016, although much of 2016 is missing, see Figure 2.15

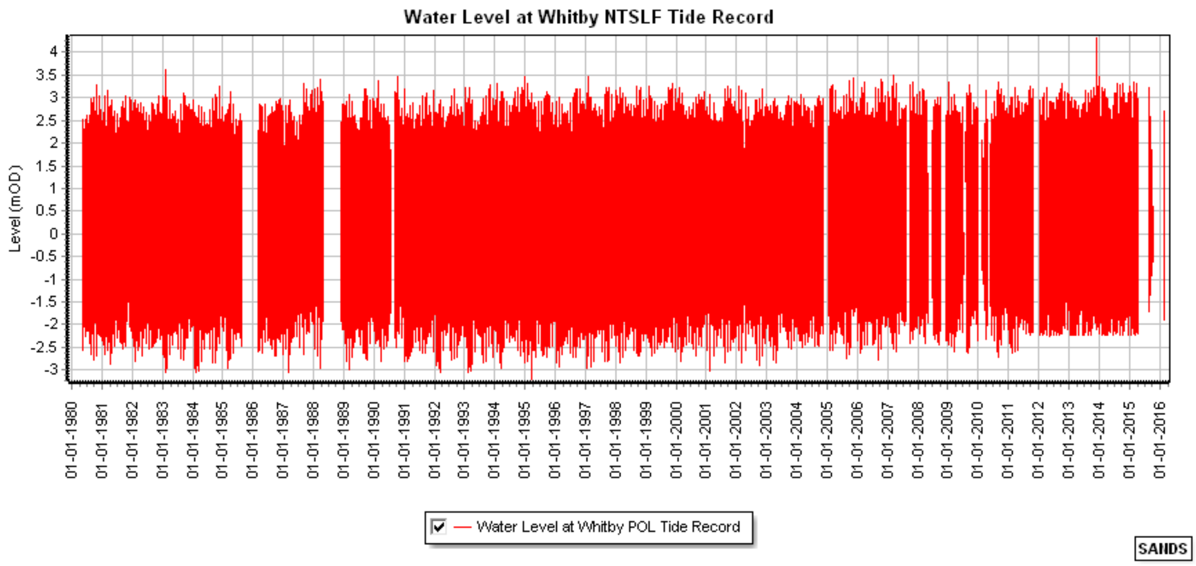


Figure 2.14 Water Level data availability at Whitby NTSLF tide gauge site

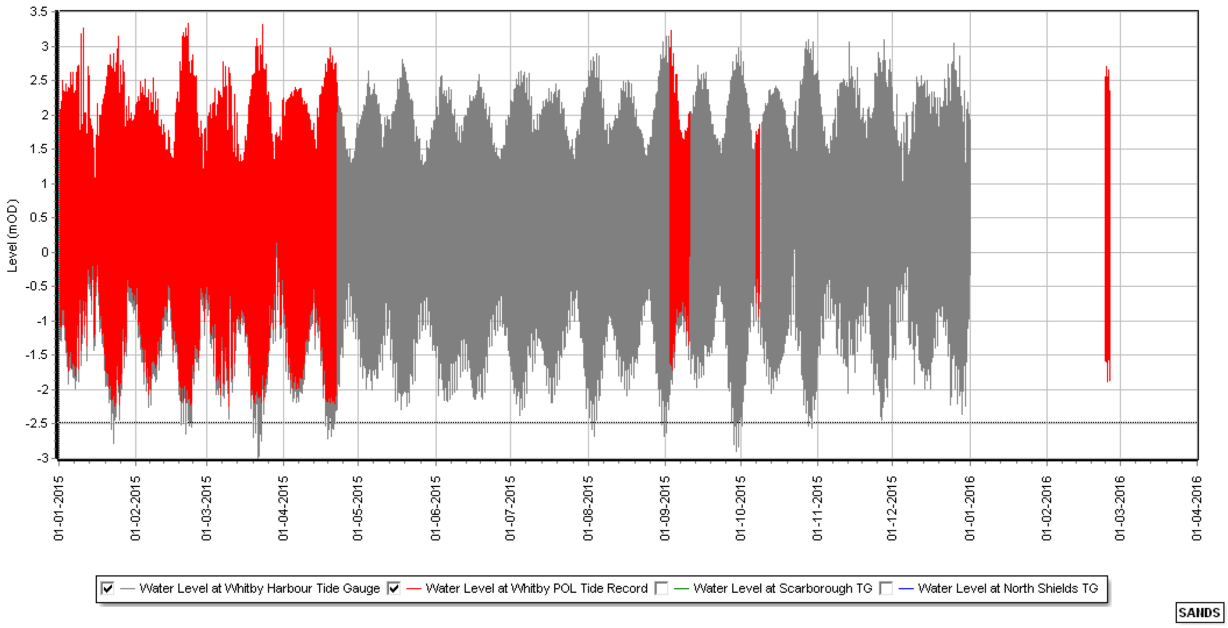


Figure 2.15 Water Level data availability for 2015/16 at Whitby NTSLF tide gauge site, also showing the Cell 1 Whitby Harbour Tide Gauge

The Whitby tide gauge data has also been used to consider the joint occurrence of high waves and high water levels as these are the most damaging events for coastal defences and most likely to precipitate coastal erosion events. The baseline report documented less than a year of data (20/05/2010 to 30/04/2011) and therefore the 2014/15 report wave data at the Whitby Waverider buoy was combined with the Whitby NTSLF data up to March 2015 to produce an updated analysis (Table 2-16). Due to the limited additional quality controlled data available for the last year (Figure 2.15) the analysis has not been updated here. As noted in the previous report, the scatter table appears to indicate a slight tendency for larger waves to occur at higher water levels and this may in part be due to depth limited wave breaking at the wave buoy, which was located in about 16m water depth. However, it is difficult to draw conclusions from the short combined record of 3.3 years' data. It is recommended that the analysis is updated when a longer concurrent data set is available.

Table 2-16 Scatter table of water level and offshore wave height at Whitby

		Water level (mOD) from NTSLF gauge at Whitby														
		-2.5	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5
		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		-3	-2.5	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2	2.5	3	3.5	4
Wave height (Hs, m) from Whitby Waverider Buoy	7.00 - 8.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.00 - 7.00	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
	5.00 - 6.00	0	0	0	1	7	2	3	7	12	11	11	8	0	0	0
	4.00 - 5.00	0	0	0	19	34	49	43	50	60	63	50	32	5	0	0
	3.00 - 4.00	0	5	15	87	140	124	141	129	150	213	130	42	2	3	4
	2.00 - 3.00	0	12	135	329	432	447	372	402	485	573	391	144	8	0	0
	1.00 - 2.00	10	159	856	1511	1968	1909	1606	1758	2128	2303	1740	675	63	0	0
	0.00 - 1.00	9	366	1937	3711	4640	4312	3763	3713	4337	4951	3500	1403	130	0	0

Water Level (x) vs Offshore Wave Height Hm0 (y) (numbers of 30 minute observations)
For date range: 20/05/2010 to 25/10/2011 and 17/01/13 to 31/03/2015 (3.3 years of data)

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 2015 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 2-17 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 2-17 Standard tidal levels at Whitby Harbour Tide Gauge (CCO, 2015)

The highest water level recorded with the Whitby Harbour Tide Gauge in 2015 was 3.18mOD on 21st February 2015.

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 2.16 and data from 2015 is presented in Figure 2.15. As noted in last year's report, comparing the derived standard tidal level data in Table 2-13 and Table 2-17, 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. As illustrated in Figure 2.16 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.

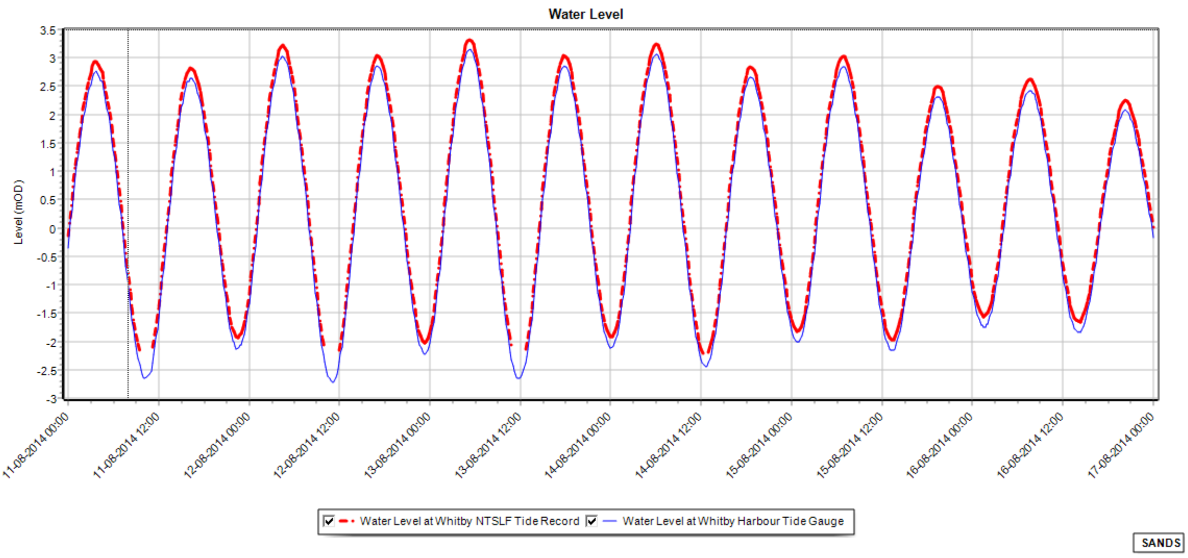


Figure 2.16 Example comparison of water level data from Whitby tide gauges

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 CCO are corresponding with NOC regarding the observed differences between the two tide gauges.

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 17th January 2013 at 54˚17.460'N, 000˚21.000'W. This is similar to the original SBC location. On 10th 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 2015 to March 2016 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 from 1st April to 13th May or from 1st June to 13th July 2015.

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 2.17 and Figure 2.18 below, respectively). The new data for the further offshore site has been overlaid on Figure 2.17 to compare to the baseline, and has also been plotted in Figure 2.19 to show fits for both peak and zero crossing period.

The new data plotted in red and green in Figure 2.17 covers the period from June 2013 to March 2015 and it is notable that the wave periods for the larger wave heights show a higher peak period than the baseline data. The 2013-14 and 2014-15 data sets show quite similar distributions. 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.

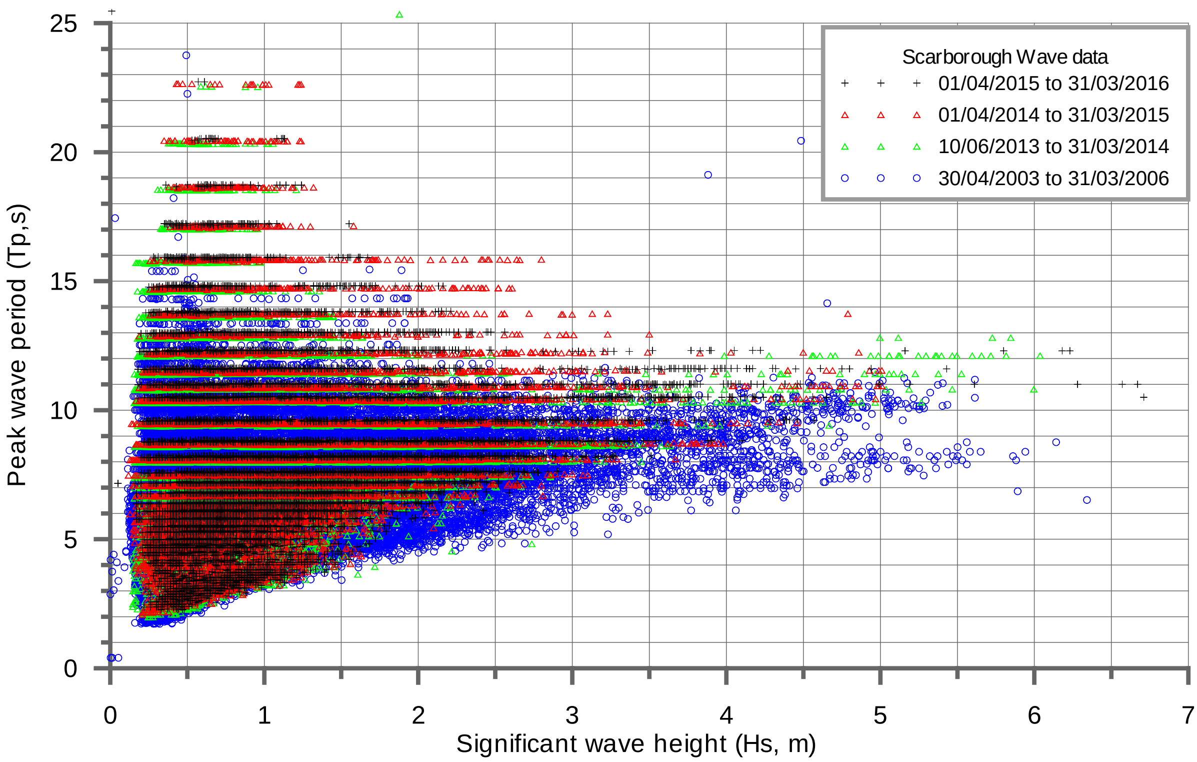


Figure 2.17 Scatter plot of Wave Height Vs Peak Period offshore Scarborough

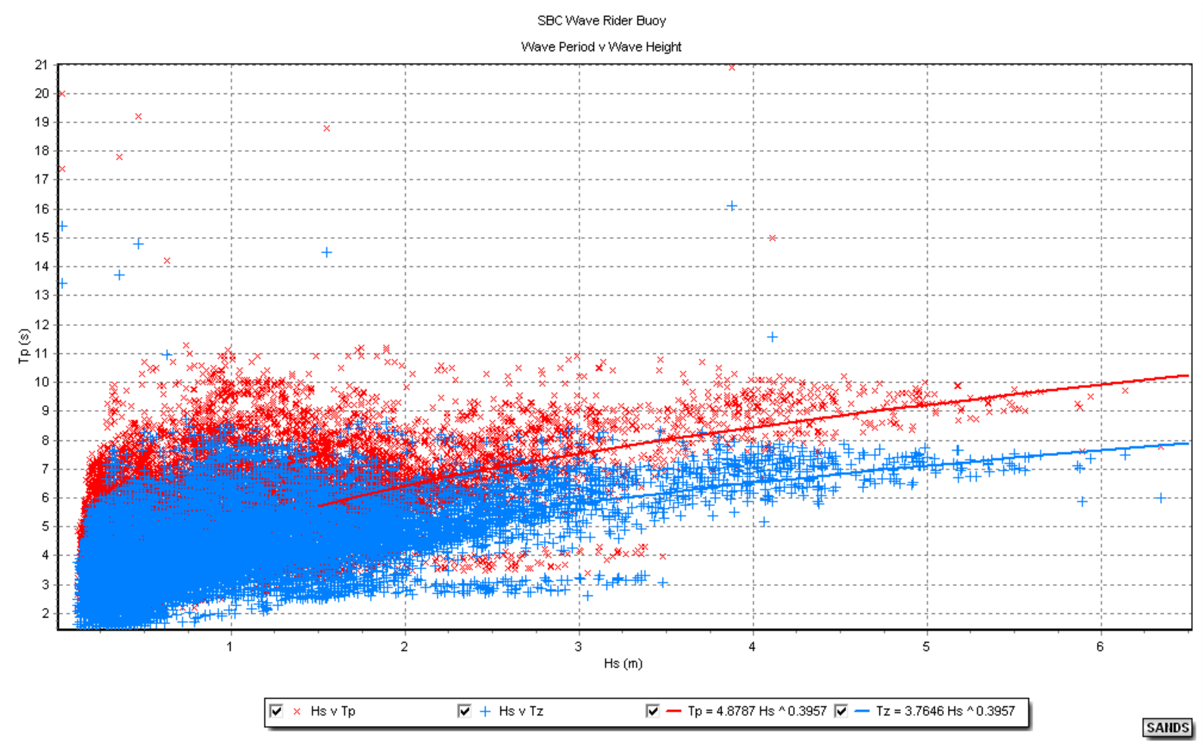


Figure 2.18 Scatter plot Wave Height Vs Period at Scarborough SBC site (April 2003 to April 2004)

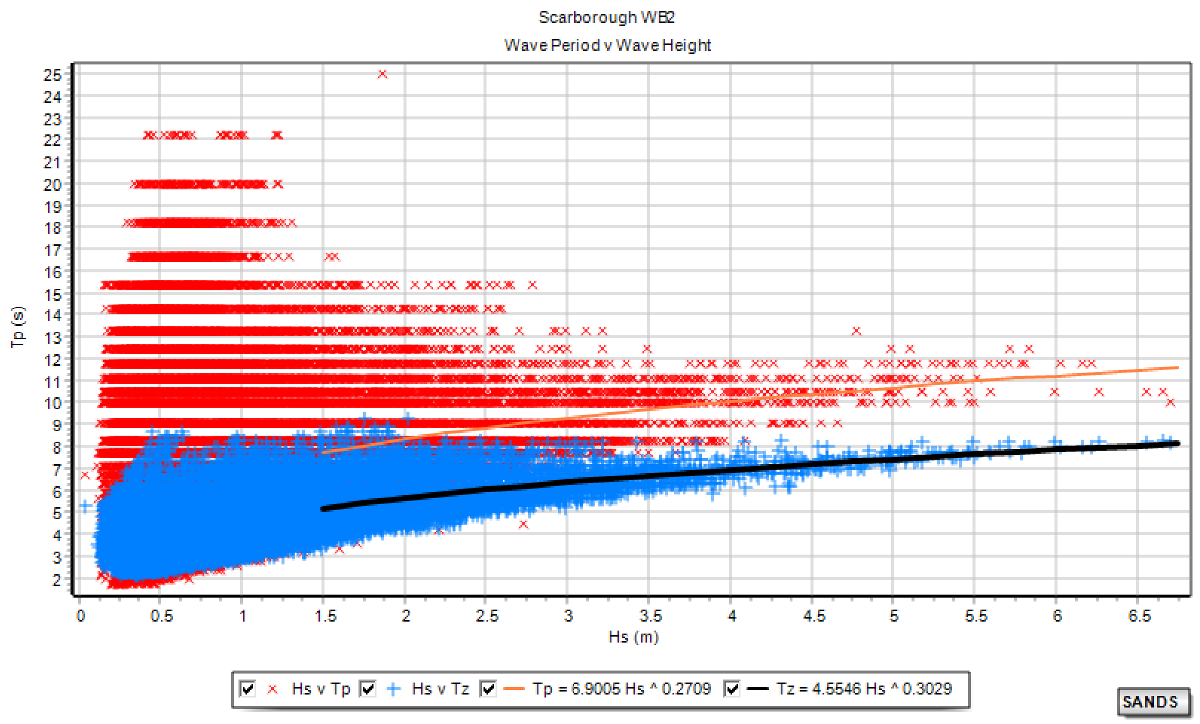


Figure 2.19 Scatter plot Wave Height Vs Period at Scarborough WB2 site (June 2013 to March 2016)

2.7.2. Wave Rose

The wave rose analysis of the baseline Scarborough DWR and SBC Waverider datasets (Figure 2.20 and Figure 2.21 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 2.22. 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.

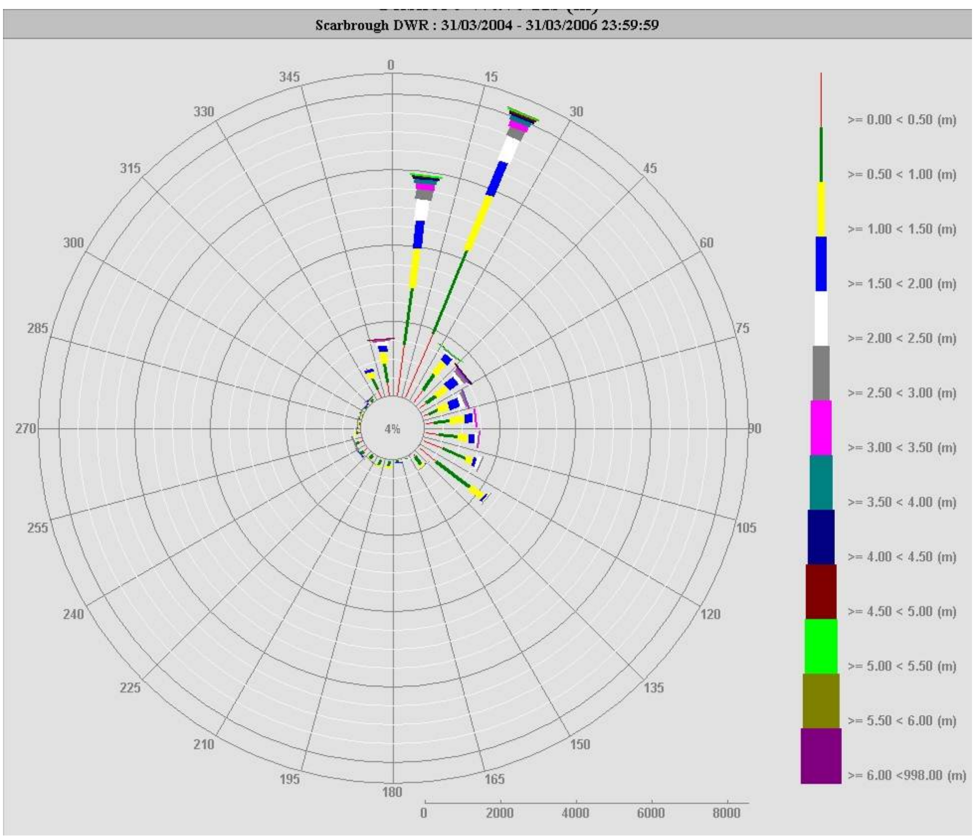


Figure 2.20 Wave Rose at Scarborough DWR site

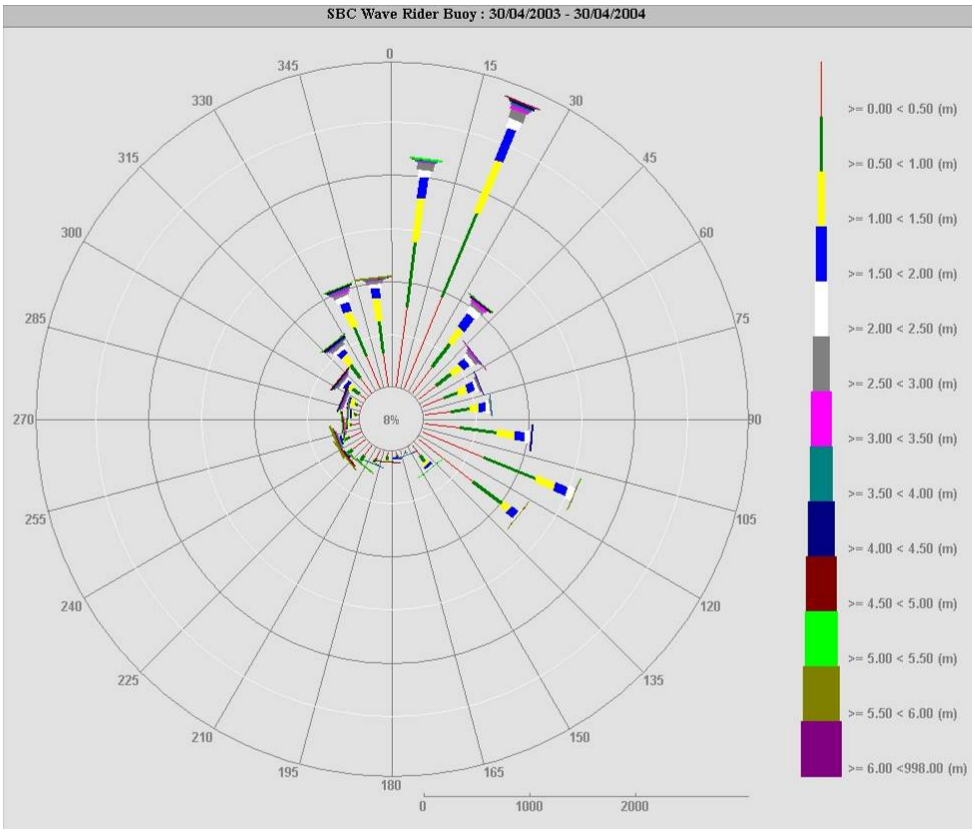


Figure 2.21 Wave Rose at Scarborough SBC site

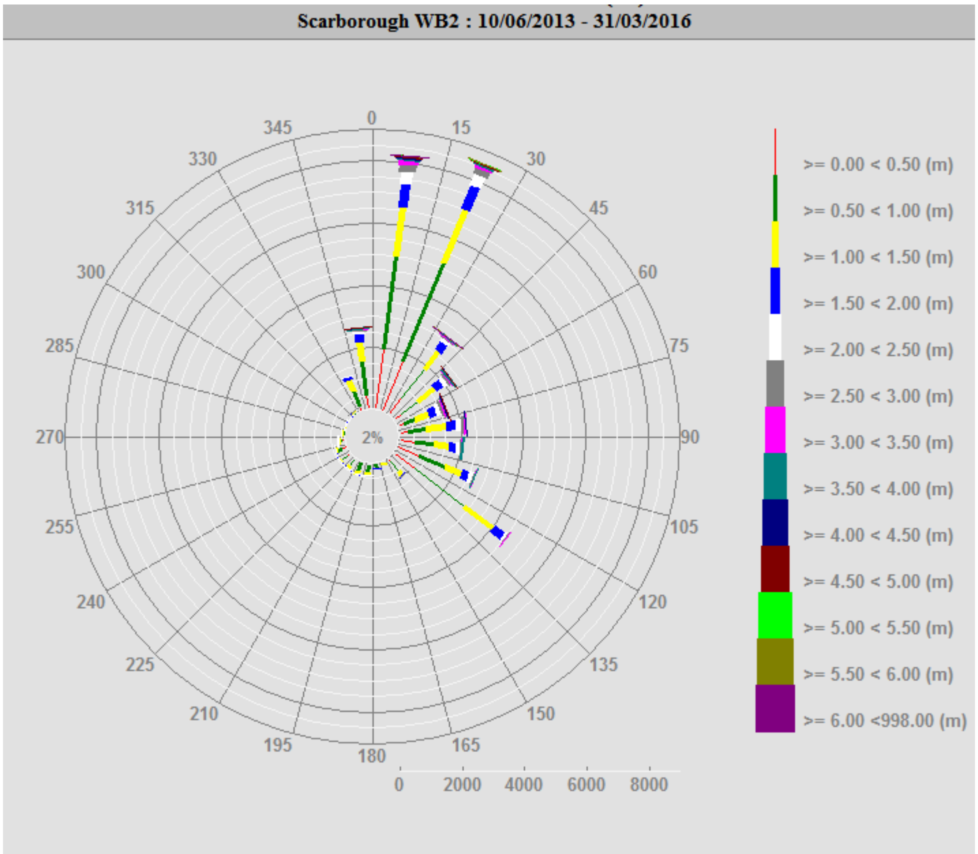


Figure 2.22 Wave Rose at Scarborough WB2 site (June 2013 to March 2016)

2.7.3. Extremes Analysis

In the baseline report the longest set of data at the Scarborough DWR buoy location was analysed to estimate extreme wave height values. A peak wave height threshold of 4m was used, providing 18 peaks in 2.92 years. The Gumbel distribution gave a reasonable correlation coefficient of 0.986 and satisfactory visual fit. Given the length of the record, the data would be unreliable beyond a 1 in 10 year return period. The new data from the Scarborough WB2 location (June 2013 to March 2016) has been analysed and a threshold of 3m gave 27 peaks in 2.8 years. The results of the extremes analysis from the baseline report and the new data from the latest deployment are shown in Table 2-18.

Table 2-18 Extremes Analysis for Scarborough wave buoys

Return Period (1 in x years)	Gumbel Fit Extreme Wave Height (Hs, m) Scarborough DWR	Gumbel Fit Extreme Wave Height (Hs, m) Scarborough WB2
0.2	4.5	3.9
0.3	4.9	4.4
0.5	5.4	5.0
1	5.8	5.7
2	6.3	6.4
3	6.5	6.7
5	6.8	7.2
10	7.3	7.8

The maximum recorded wave height (Hs) in the data recorded at the Scarborough WB2 location is 6.7m on the 21st November 2015, which compares to the previous largest wave height of 6.0m on 10th October 2013. Comparing these to the baseline extremes analysis indicates that they were approximately equal to the 1 in 3 year event and the expected worst annual storm respectively.

2.7.4. 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 2-19 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.

Table 2-19 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 $L_o = g.Tp^2/2.\pi$

Storms analysis from the new Waverider buoy deployed offshore from Scarborough as part of the current programme in January 2013 is provided in Table 2-20 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 October 2013 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. Similarly to the situation at Whitby, there was only one storm identified during 2014; at Scarborough the peak wave height was 4.4m and duration only 3 hours. The only storm recorded during winter 2014/15 had a peak wave height of 4.8m and 28 hour duration.

Table 2-20 Storm analysis for Scarborough WB (data 17/01/2013 to 31/03/2016)

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

Note * = data missing from record during early part of storm on 21/11/2015

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 available from the Scarborough tide gauge record is shown in Figure 2.23 below. The data runs from 28/04/2003 to 31/12/2014, with a number of gaps in the record. A more detailed plot showing the data available for 2015 is shown in Figure 2.24.

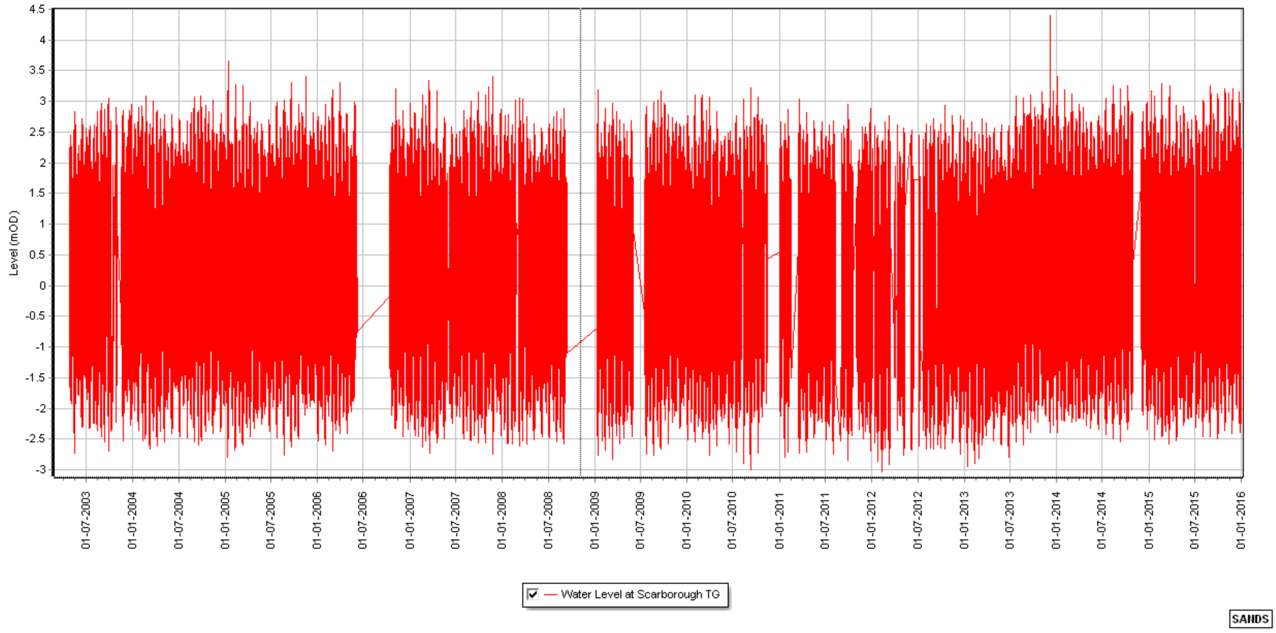


Figure 2.23 Water Levels at Scarborough TG Recorded Tide Site

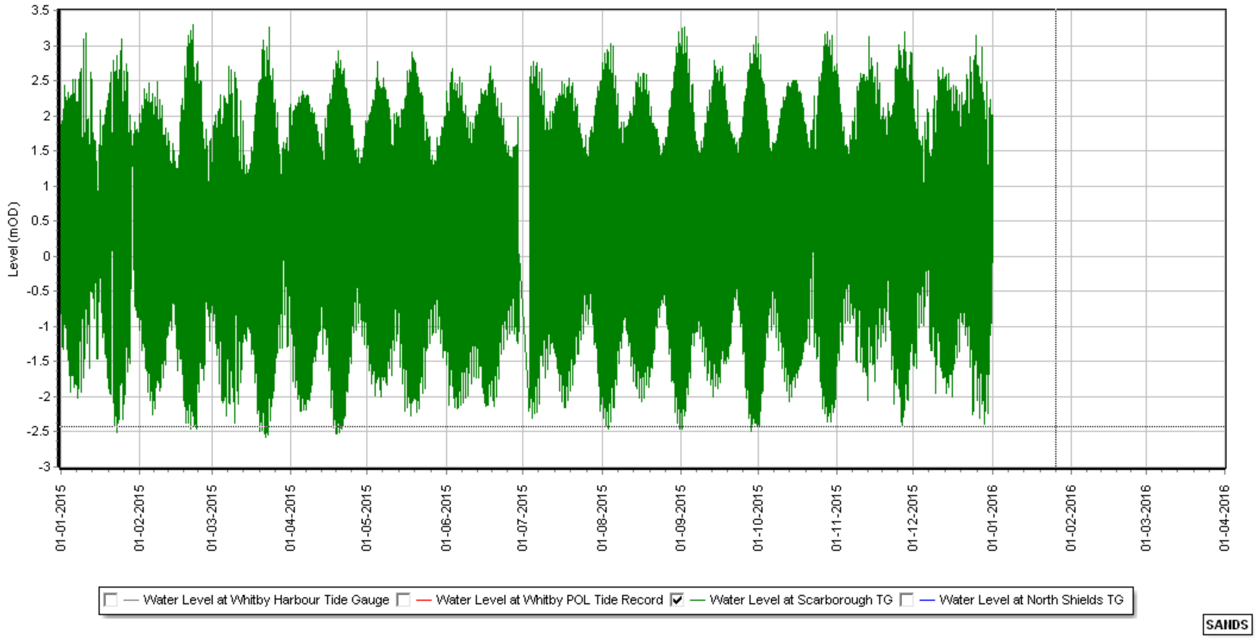


Figure 2.24 Water Levels at Scarborough TG Recorded Tide Site for 2015-16

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 2-21 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 2-21 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 2-22 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. Comparing the measured water level of the 5th December 2013 surge to the predicted extremes from the EA's 2011 Coastal Flood Boundary (CFB) conditions data in Table 2-23 shows that the event had an annual exceedance probability of between 1 in 150 and 1 in 500.

The ten years of water level data from the Scarborough tide gauge prior to the December 2013 storm surge were previously analysed in SANDS to derive extreme levels to compare to the EA 2011 CFB data. The Peak over Threshold approach was used, with a threshold of 2.2m and data bins of 0.1m. The results, which had a good correlation coefficient of 0.996 for the Gumbel fit, are given in the second from right column in Table 2-23 and are very similar to the results of the EA CFB study in the second column from the left. The analysis has been updated for this report to include all data recorded at the gauge, and results are presented in the right hand column of Table 2-23, showing that inclusion of the 2013 surge event increases the extreme water level estimates by around 0.2m. Note that the confidence levels for the EA CFB data should also be assumed to apply to the local data analysis with SANDS. The set of return periods derived in SANDS is different to the EA CFB study so results are not available to compare for all return periods.

Table 2-22 Annual maxima data from Scarborough Tide gauge (source CCO, 2016)[2]

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

The water level data has also been used to analyse joint occurrence of waves and water levels by tabulating the frequencies of coincident wave and water level measurements, see Table 2-24 below.

In the baseline report the water level and wave height analysis required post-processed interpolation to derive water level at the same times as the wave height data. The data has now been reprocessed and quality controlled by CCO (see report in Appendix E), which made the analysis more straightforward in SANDS for the 2015-15 report. The analysis has been updated for this report to include data for 2015. Note that this analysis uses the wave data only from the further offshore location as this is the location where there is most data available, and this is the current location of the Scarborough wave buoy. Note that the data excludes the 5th December 2013 storm surge because there is a gap in wave the data set whilst wave buoy was off station between 21st November 2013 and 17th December 2013. There are also a considerable number of other gaps in the matched wave / water level data set, as the total merged record length is equivalent to just 3.1 years. This analysis supersedes that presented in the previous Cell 1 wave and tide reports.

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

Table 2-23 Predicted extreme tide levels at Scarborough

Annual Exceedance probability	Extreme Level (m OD) from EA CFB Study (2011)[1]	Confidence intervals (m) from EA CFB Study (2011)[1]	Extreme levels from SANDS analysis of Scarborough TG (mOD)[2]	Extreme levels from SANDS analysis of Scarborough TG to Dec 2015 (mOD)[3]
1 in 1	3.39	0.1	3.3	3.5
1 in 2	3.48	0.1	3.4	3.6
1 in 5	3.60	0.1	3.6	3.8
1 in 10	3.70	0.1	3.7	4.0
1 in 20	3.80	0.1	3.8	4.1
1 in 25	3.84	0.2		
1 in 50	3.95	0.2	4.0	4.3
1 in 75	4.00	0.2		
1 in 100	4.04	0.3	4.1	4.5
1 in 150	4.12	0.3		
1 in 200	4.17	0.3	4.2	4.6
1 in 250	4.20	0.3		
1 in 300	4.23	0.4	4.3	4.7
1 in 500	4.33	0.4		
1 in 1,000	4.45	0.5		

Notes: (1)data from EA (2011), Chainage 3750
http://evidence.environment-agency.gov.uk/FCERM/en/Default/FCERM/Project.aspx?ProjectID=F162D56F-87C4-4F14-B77B-A8A3EFDB363F&PageId=a0fe6dfc-506a-452c-9bff-a7ec06b4e6b0
(2) Data to end of November 2013, results taken from 2013-14 report, Excludes the Dec 2013 storm.
(3) Data to end of December 2015, analysis for this report

Table 2-24 Scatter table of water level and wave height at Scarborough

	Water level (mOD) at Scarborough TG													
	-2.5 - -3.0	-2.0 - -2.5	-1.5 - -2.0	-1.0 - -1.5	-0.5 - -1.0	0.0 - -0.5	0.5 - 0.0	1.0 - 0.5	1.5 - 1.0	2.0 - 1.5	2.5 - 2.0	3.0 - 2.5	3.5 - 3.0	4.0 - 3.5
Wave Height (Hs,m)														
7.00 - 8.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.00 - 7.00	0	0	0	0	1	2	1	2	1	0	1	0	0	0
5.00 - 6.00	0	0	0	5	12	8	7	6	11	10	12	7	0	0
4.00 - 5.00	0	2	4	22	46	27	29	29	26	36	24	18	1	0
3.00 - 4.00	0	5	30	68	84	72	65	71	96	117	78	20	4	0
2.00 - 3.00	4	33	173	291	400	339	317	353	424	432	269	61	3	0
1.00 - 2.00	28	386	1162	1576	1805	1624	1531	1676	2071	1960	1439	436	32	0
0.00 - 1.00	26	886	2284	3700	4251	3744	3328	3642	4394	4388	2637	1013	75	0

Water Level (x) vs Offshore Wave Height Hm0 (y) (numbers of 30 minute observations)
Data range: 31/04/2004 to 19/07/2004 and 10/06/2013 to 31/12/2015 (3.1 years data when accounting for gaps)

3. Discussion of variability in waves and water levels and longer term trends

3.1. Data availability

The wave and water level monitoring data collected under the Cell 1 programme are starting to build a record that will improve the understanding of the variability and trends in storm waves and water levels. However the duration of the data collection through the Cell 1 programme is fewer than ten years for most sites. The length of the data records within Cell 1 are identified in Table 3-1 below.

Table 3-1 Duration of data sets in Cell 1 and comments on reliability

Name of Location	Type of Data	Data period	Comments
Newbiggin Ness WB	Wave Data	20/05/2010 to 07/06/2011 and 21/06/2013 - ongoing	About 4 years' data available, not yet sufficient to identify typical annual variability or for trends analysis
North Shields NTSLF Tide Record	Tidal Levels	Intermittent data since 24/01/1946 Monthly and annual mean data from 1895 to present	One of the longer tide gauge records for the UK. Monthly and annual mean sea level data has previously been analysed to identify long term sea level trends, **see Section 3.2**
North Shields GPS tide gauge monitoring	Land levels	1997 to 2014	Land level monitoring data from the tide gauge station, allows removal of land level change from tide gauge mean sea level change records, **see Section 3.1**
Tyne Tees WaveNet Site (WMO ID 62293)	Wave Data	07/12/2006 - ongoing	About 10 years of data available, **see Section 3.3**
Met Office WWIII model	Wave data	1980 – ongoing	Up to 35 years' data now available. Data for 1980 to 2012 was reported on in the 2013-14 report. **See also Section 3.3**
Whitby WB	Wave Data	20/05/2010 to 04/11/2011 and 17/01/2013 - ongoing	About 4 years' data available, not yet sufficient to identify typical annual variability or for trends analysis
Whitby NTSLF Tide Record	Tidal Levels	Digital data from 1991 – ongoing and monthly and annual mean data from 1981 - ongoing	Monthly and annual mean sea level data has previously been analysed but found unreliable for to identifying long term sea level trends, **see Section 3.4.** Issues with tide gauge datum, siltation, omission of extreme low waters and unexplained high rate of sea level rise.
Whitby Harbour Tide Gauge	Tidal Levels	16/01/2014 - ongoing	About 30 months of data. Close proximity to Whitby NTSLF gauge, very similar signal but about 0.18m datum level difference.
Scarborough Wave buoys	Wave Data	2003 – 2006 and 2013 - ongoing	A total of about 5 years of data available, not yet sufficient to identify typical annual variability or for trends analysis. Changes in the location result in data not being fully consistent. Comparison of data from current programme to the older baseline data indicates that there may be an issue

Name of Location	Type of Data	Data period	Comments
			with some of the wave periods in the 2003 – 2006 data.
Scarborough TG	Tidal Levels	28/04/2003 - ongoing	Uncertainty over possible datum changes during period when gauge was not maintained between 2006 and 2011

3.2. North Shields tide record

The tide gauge data from North Shields is one of the longer UK data sets and has been analysed by a number of researchers investigating long term trends in mean sea level. In addition to the digital data identified through NTSLF in Table 1-1, annual mean data are available from 1901 through the PSMSL in Table 3-1.

Trend analysis for mean sea level at North Shields is reported in Woodworth et al. (2009)[3]. Their analysis used data from 1901 to 2006 and found a long term trend of 1.92 ± 0.12 mm/yr. They also provide estimates of long term land level changes at tide gauges based on Shennan and Horton (2002)[4], with an estimate of 0.0 mm/yr for North Shields based on geological data, not GPS land level monitoring. Woodworth's analysis was careful to only include years that had data for all months in order to remove seasonal impacts. The latest published monthly and annual data for North Shields has been downloaded from the PSMSL website http://www.psmsl.org/data/obtaining/stations/95.php and is plotted in Figure 3.1 below. At the time of writing (May 2016) the data for 2015 had not been made available. In Figure 3.1, the linear fitted trend for all of the annual data shows a rate of rise of 1.903 mm/yr whilst the trend for all of the monthly data shows a trend of 1.911 mm/yr.

GPS ground level monitoring is also undertaken at the North Shields tide gauge and data for 1998 to 2009 were downloaded and added to Figure 3.1. This indicates land levels were rising at the tide gauge by around 0.6mm/yr over this short period and this therefore implies a total 2.5mm/yr net mean sea level rise. The GPS data shown in Figure 3.1 are for station "nstg" and according to the detailed analysis provided by the NERC British Isles continuous GNSS Facility (BIGF), see Figure 3.2, the trend has an uncertainty of +/- 0.8mm/yr. The tide gauge was relocated in 2010 and GPS data for the new location, see dataset "nslg" in Figure 3.2 shows a lower, 0.1+/-0.7mm/yr rate of rise since 2010.

[3] P.L. Woodworth, F.N. Teferle, R.M. Bingley, I. Shennan and S.D.P. Williams, Trends in UK mean sea level revisited, Geophys. J. Int. (2009) 176, 19–30.
[4] Shennan, I. & Horton, B., 2002. Holocene land- and sea-level changes in Great Britain, J. Quat. Sci., 17, 511–526, doi:10.1002/jqs.710.

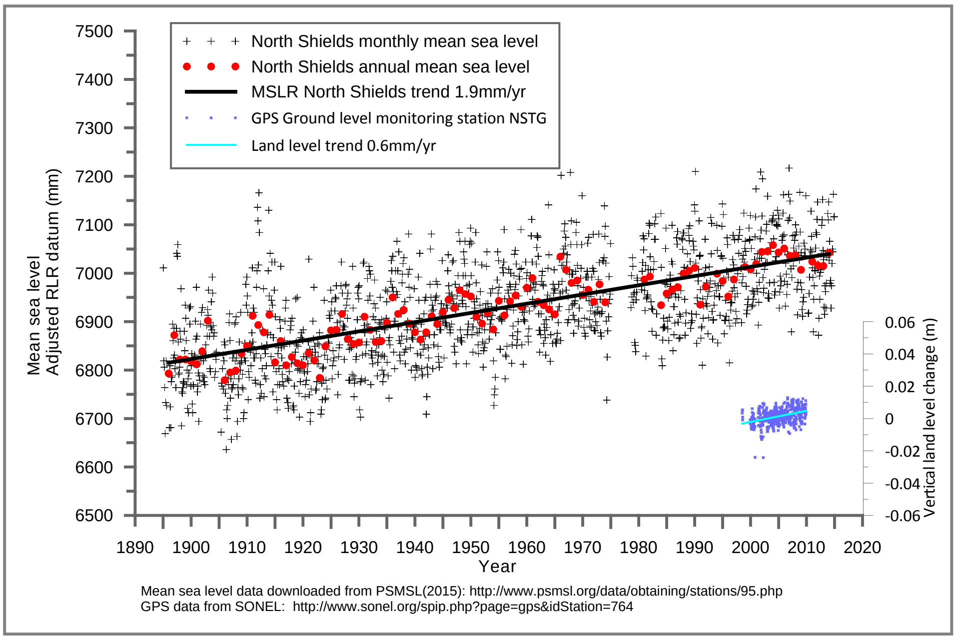
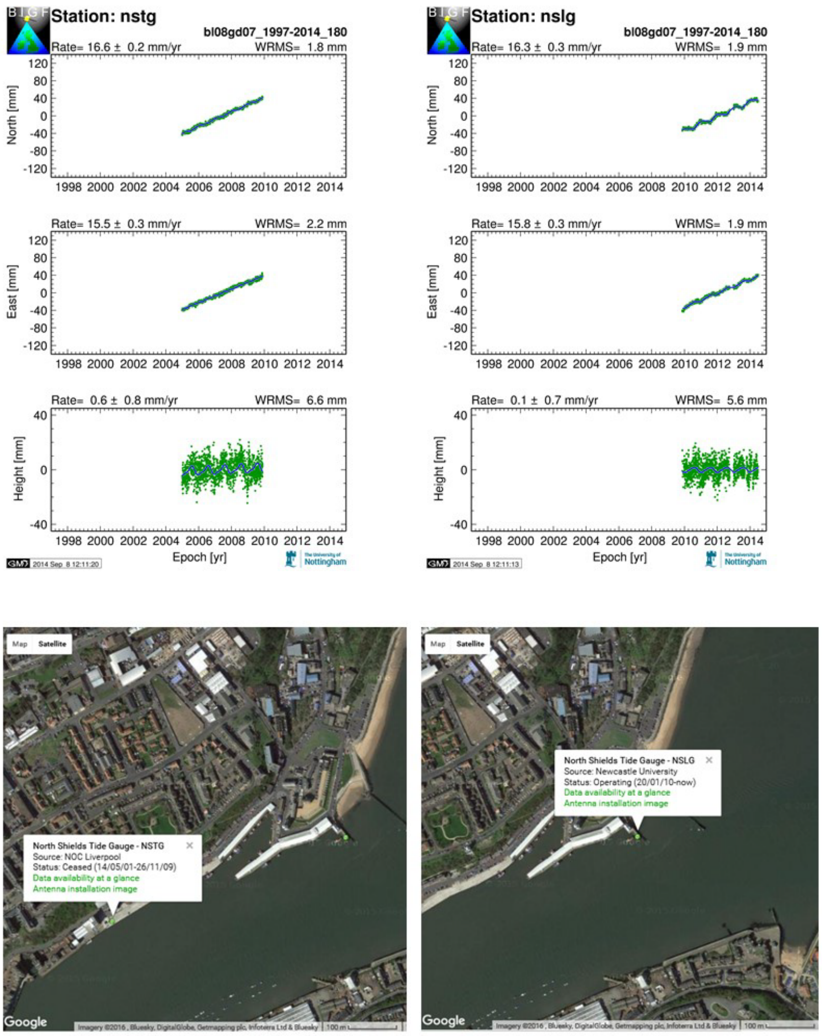


Figure 3.1 Annual and monthly mean sea level data for North Shields, 1895 to 2015



Data provided by NERC British Isles continuous GNSS Facility, BIGF at the University of Nottingham, http://www.bigf.ac.uk/data_availability

Figure 3.2 Tide gauge GPS monitoring data from BIGF for station nstg/nslg

3.3. Tyne / Tees Wavenet site

Measured wave data from the Cefas offshore WaveNet site covers about nine years. Whilst this is shorter than the 30 year period typically used to define average climates it is the longest consistently measured offshore wave record for the Cell 1 coast. To assess the annual variability of storms, Figure 3.4 below compares the annual maximum peak storm wave heights from the Tyne Tees buoy over the measured record length to the data from the Met Office WWIII model from 1980 to 2012 that was obtained for the 2013-14 report. There is a lot of scatter in both data sets. The variability in the shorter period of measured data does not appear unrealistic in the context of variability of the much longer set of modelled data. The fitted line to the 33 years of modelled data shows a very slight upward trend in annual maximum wave heights. However, as demonstrated by the fitted trend line for the shorter data set, the annual variability is so much larger than any annual trend that the fitted trend line for the Tyne Tees data set is totally unrealistic.

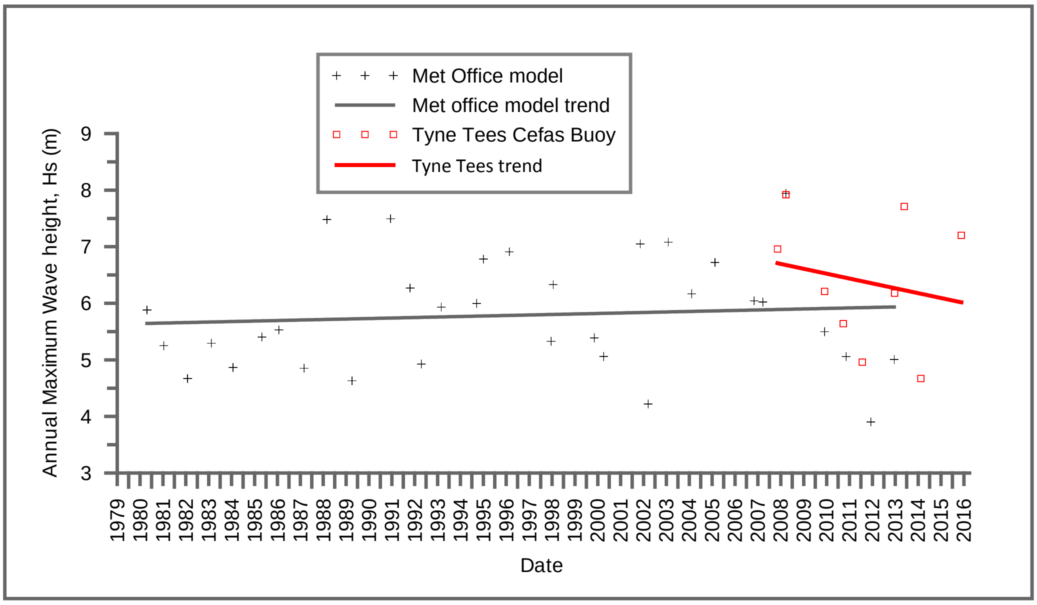


Figure 3.3 Annual maximum wave height from Met office model and Tyne Tees Buoy

3.4. Whitby tide record

Tide gauge data at Whitby NTSLF is available since 1980. However, it was noted by Woodworth et al (2009)[3] to be unreliable for mean sea level trend analysis because the PSMSL documentation made clear that the data were of poor quality. The rate of vertical land level change reported by Woodworth at Whitby is −0.48mm/yr, although this is estimated by interpolation from geological data, not GPS land level monitoring.

The annual and monthly mean data for the Whitby site was downloaded from PSMSL and is plotted in Figure 3.4. This shows an annual trend of +7.1mm/year, which is not consistent with other longer term tide gauges in the UK, e.g. the rate at Immingham on the Humber given by Woodworth is 0.54 ± 0.39 mm/yr and the long term rate of change at North Shields is 1.9mm/yr; see Figure 3.1.

The PSMSL documentation for the Whitby tide gauge records http://www.psmsl.org/data/obtaining/stations/1505.php mentions multiple problems at the site, with several statements that the gauge recorded “flat low-waters”. This is taken to mean that the gauge does not always measure the full tidal range due to sedimentation or blockage. Removing low water values from the data would result in spuriously high mean sea levels, possibly explaining at least part of the erroneous rate of rise of the derived mean sea level. The PSMSL site also says to treat data from 1997 onwards as “suspect”.

The annual mean data for Whitby were also analysed to determine rate of change over shorter periods; data from 1980 to 1997 indicate a trend of 2.1mm/yr. If 180mm is removed from data from 2012 to 2014, based on the finding that the NTSLF gauge data is 0.18m higher than the Cell 1 Whitby gauge in 2014, the overall rate of rise would be about 3.0mm/yr. This suggests that the datum problem may be with the NTSLF gauge rather than the Whitby Cell 1 gauge.

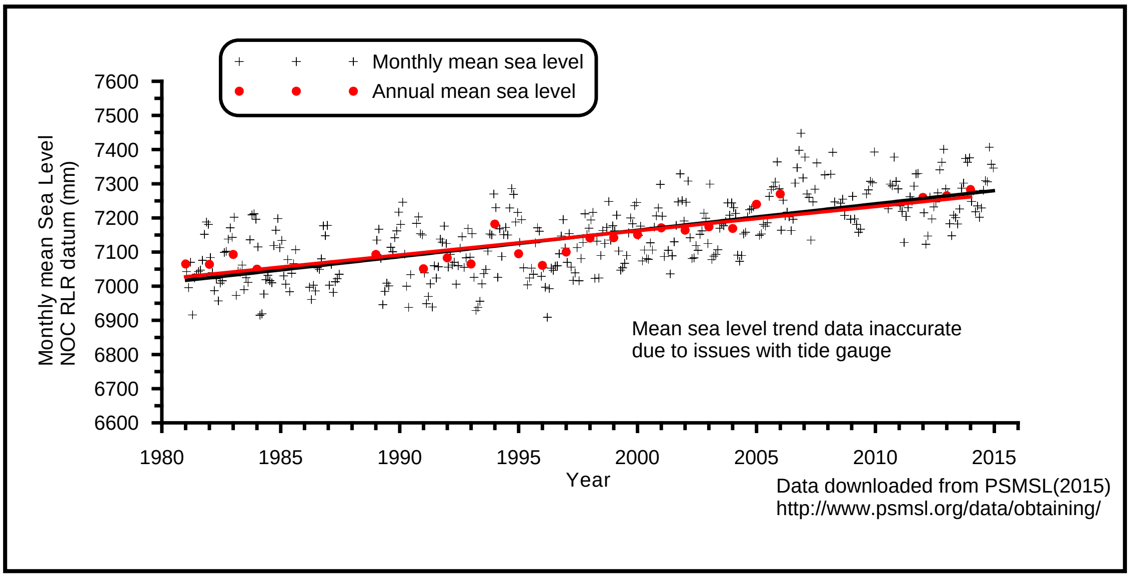


Figure 3.4 Annual and monthly mean sea level data for Whitby, 1980 to 2015

4. Problems encountered and uncertainty in analysis

4.1 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 Newbiggin Ness wave buoy data has a short gap in the data of about four days during January 2016 whilst the wave buoy was off station following an incident.

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 August 2015. However, there were two significant gaps in the post-processed data (20/01/2007 to 13/02/07 and 21/01/2008 to 08/04/2009) that were filled by telemetry data as well as from August 2015 to March 2016. The data set analysed is therefore a combination of telemetry and post recovery data, to give greatest coverage.

There are several significant gaps in the Whitby Waverider buoy data whilst the buoy was off station due to damage. This includes 8th May to 13th May, 17th May to 23rd July and from 17th to 21st October and also small gaps in November 2015 and January 2016.

The Scarborough Waverider was off station due to several incidents during the year and no data are available from 1st April to 13th May or from 1st June to 13th July 2015.

4.2 Water level data

There were some significant gaps in the data from the North Shields tide gauge, e.g. from 26/04/15 to 02/05/15 and 9/10/15 to 29/10/15 where the BODC QC had flagged the data with an 'M' as 'improbable'. There were also large gaps or suspect records in the data from 04/01/16 to 13/01/16.

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 recommended in the previous report, the datum level surveys should be checked for both of the Whitby tide gauges to establish which is correct and if possible the data should be corrected.

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.

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 2.16.

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.

5. Summary of key findings and recommendations

This report has analysed new wave and water level data available relevant to coastal Cell 1 for 2015-2016 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 2015-16 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 2014 data from Tyne Tees indicates that the stormiest year was 2010 whilst the year with the least number of storms is 2015. 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 2015-16 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 the 21st Nov 2015.
- The storm surge that occurred in early December 2013 resulted in higher water levels than previously observed in Cell 11, exceeding the 1953 storm at North Shields. As demonstrated in the 2013-14 report, inclusion of data from the December 2013 storm in extreme water level analysis results in extreme levels increasing by 100mm to 200mm. As noted in the 2013-14 and 2014-15 report it is recommended that the extreme water level statistics for the whole of Cell 1 are revised to take the December 2013 event into account for future predictions. It is understood that the Environment Agency are planning to undertake a study to update their national dataset, with a possible planned start in 2016.
- 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, Tyne Tees, Whitby, Scarborough DWR and Scarborough SBC are collated in Figure 5.1 to supplement the points made above. Wave height data over the period April 2015 to March 2016 for the four Cell 1 wave buoys are also shown in Figure 5.2 to illustrate the data availability.

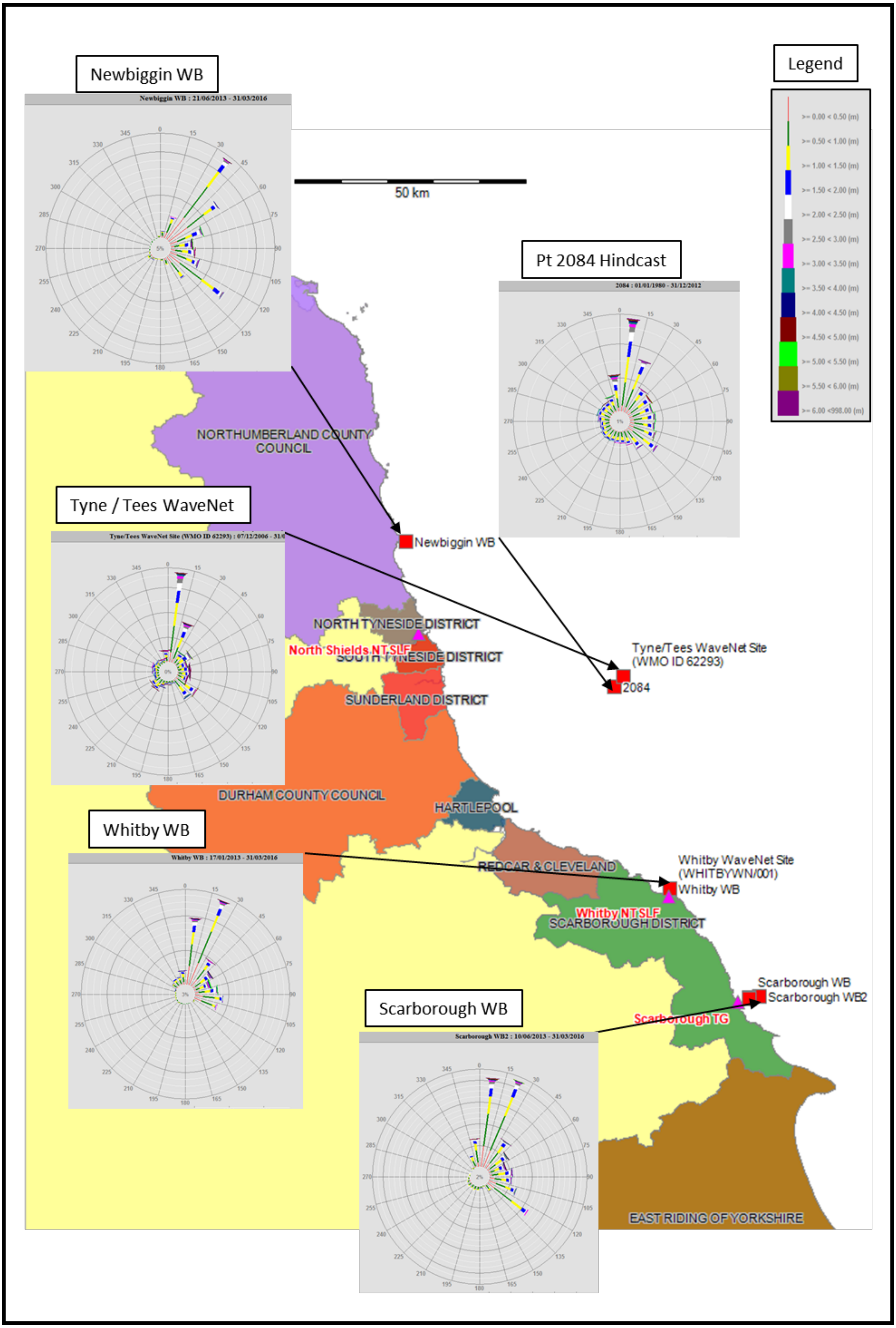


Figure 5.1 Wave Rose Locations from Newbiggin Ness to Scarborough

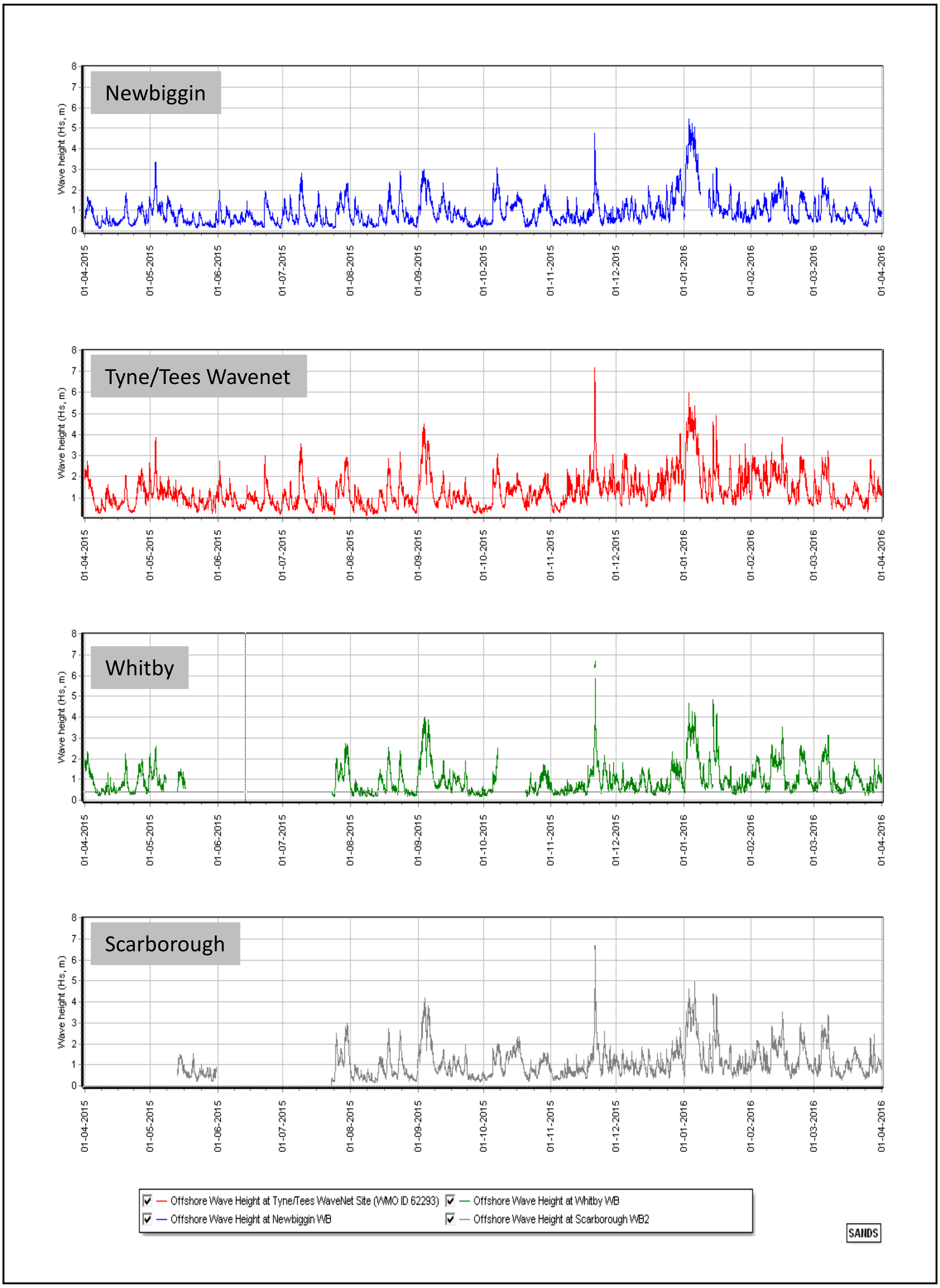


Figure 5.2 Wave height data for 2015-16 in Cell 1

6. 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 2015-16 than in previous years, the largest wave heights recorded to date occurred in November 2015 at Whitby and Scarborough and in early January at Newbiggin. Wave conditions during the period from February 2014 to March 2015 were notably less stormy than the previous years.

As noted in the 2013-14 report it is recommended that the extreme water level statistics for the whole of Cell 1 are revised to take the December 2013 event into account for future predictions. It is understood that the Environment Agency are planning to undertake a study to update their national extreme water level dataset, known as the coastal flood boundary (CFB) conditions, with a possible planned start in 2016.

Appendices

Appendix A

Detailed Location of Wave Buoys

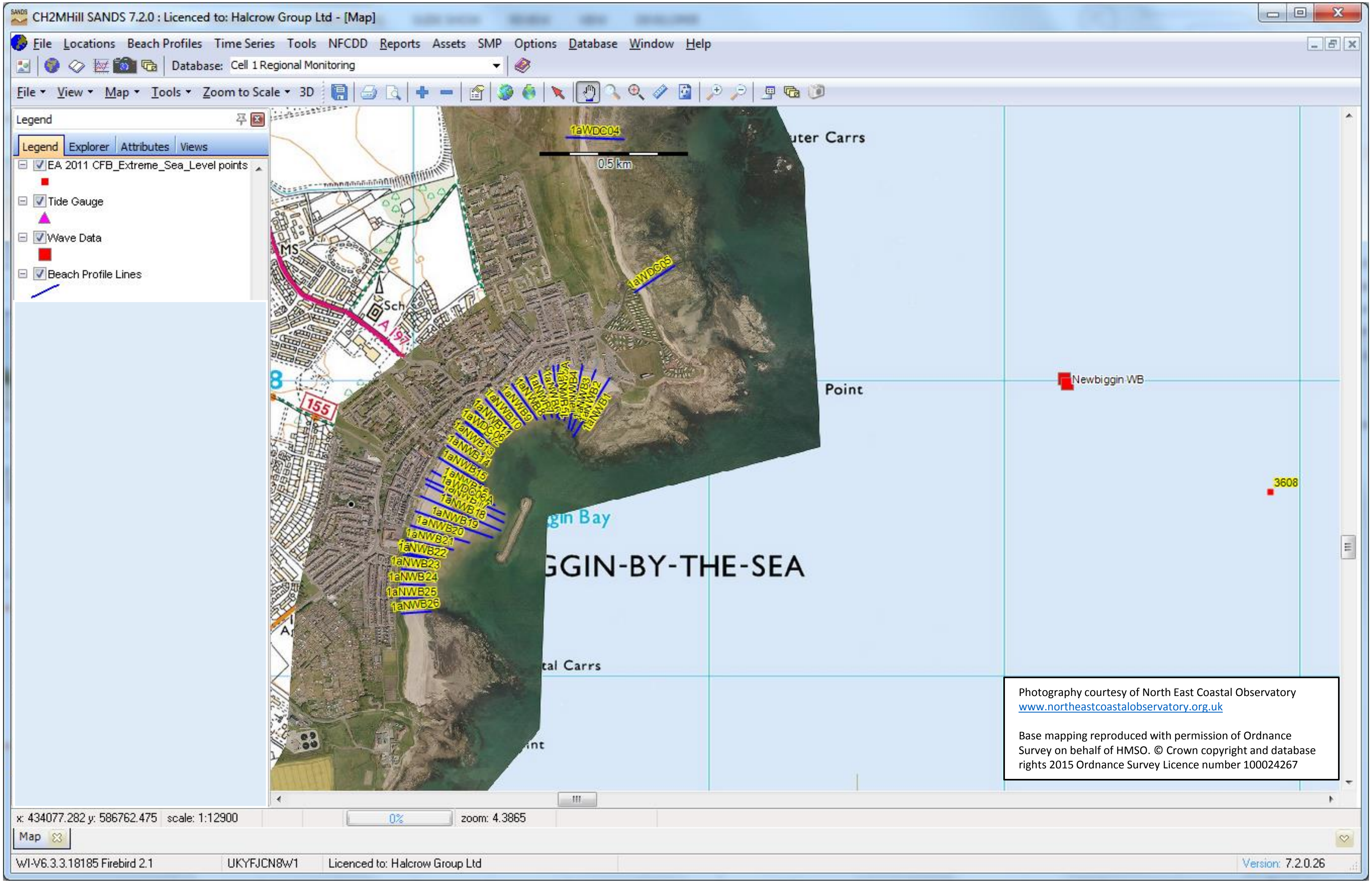


Figure A1 Location of Newbiggin Ness wave buoy

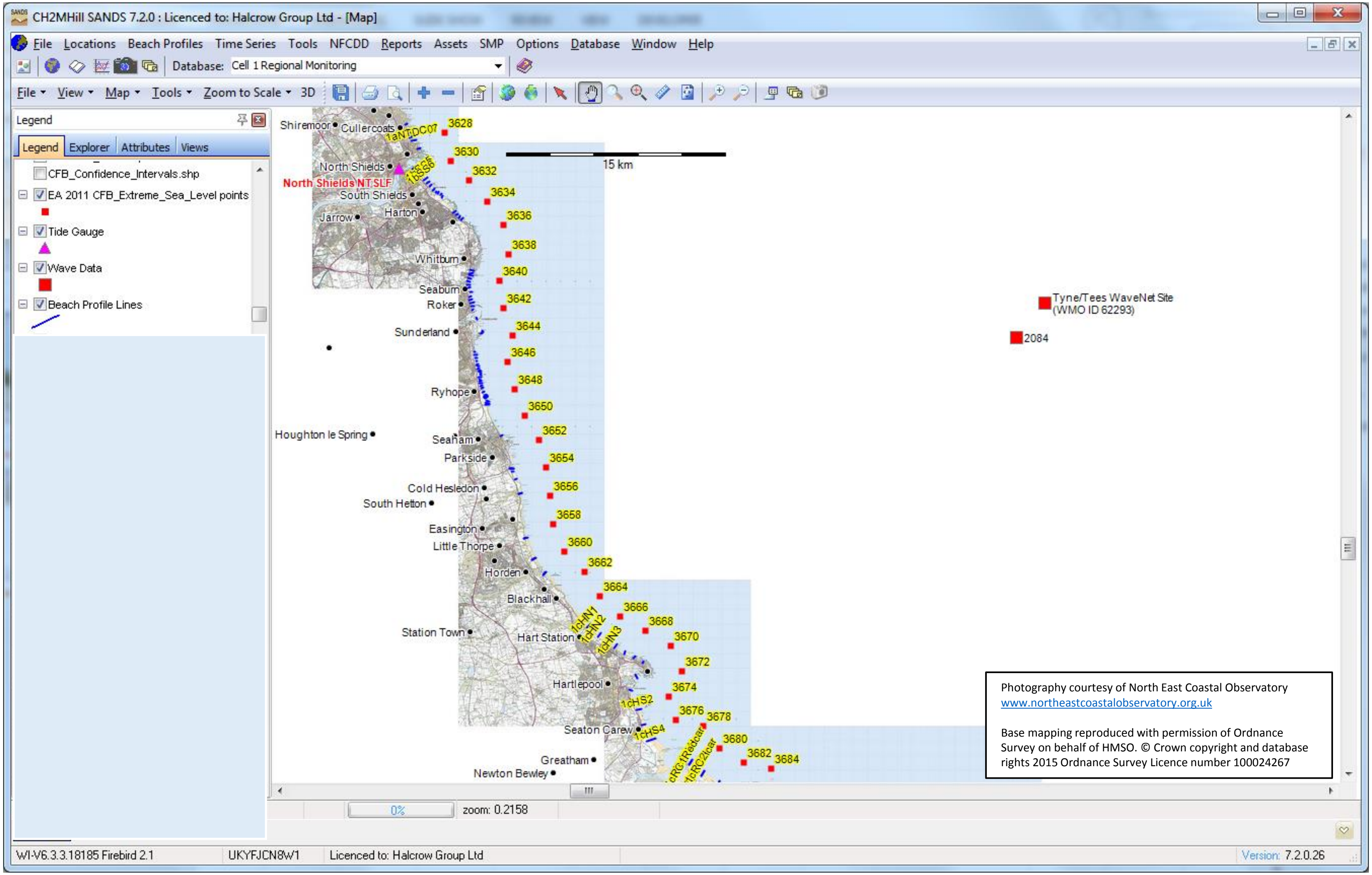


Figure A2 Location of Tyne Tees wave buoy, Met Office hindcast point 2084 and North Shields tide gauge

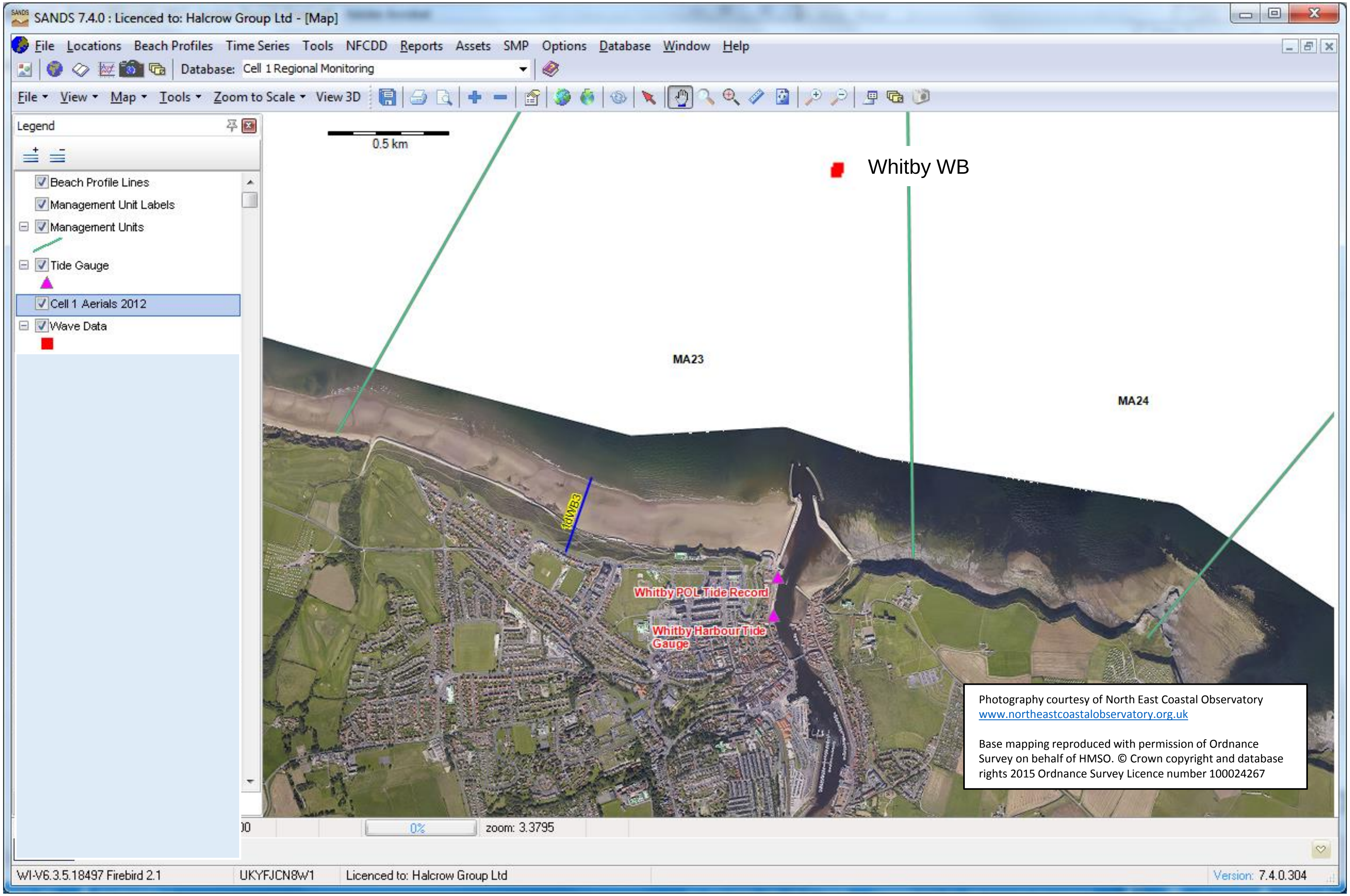


Figure A3 Location of Whitby wave buoy and tide gauges

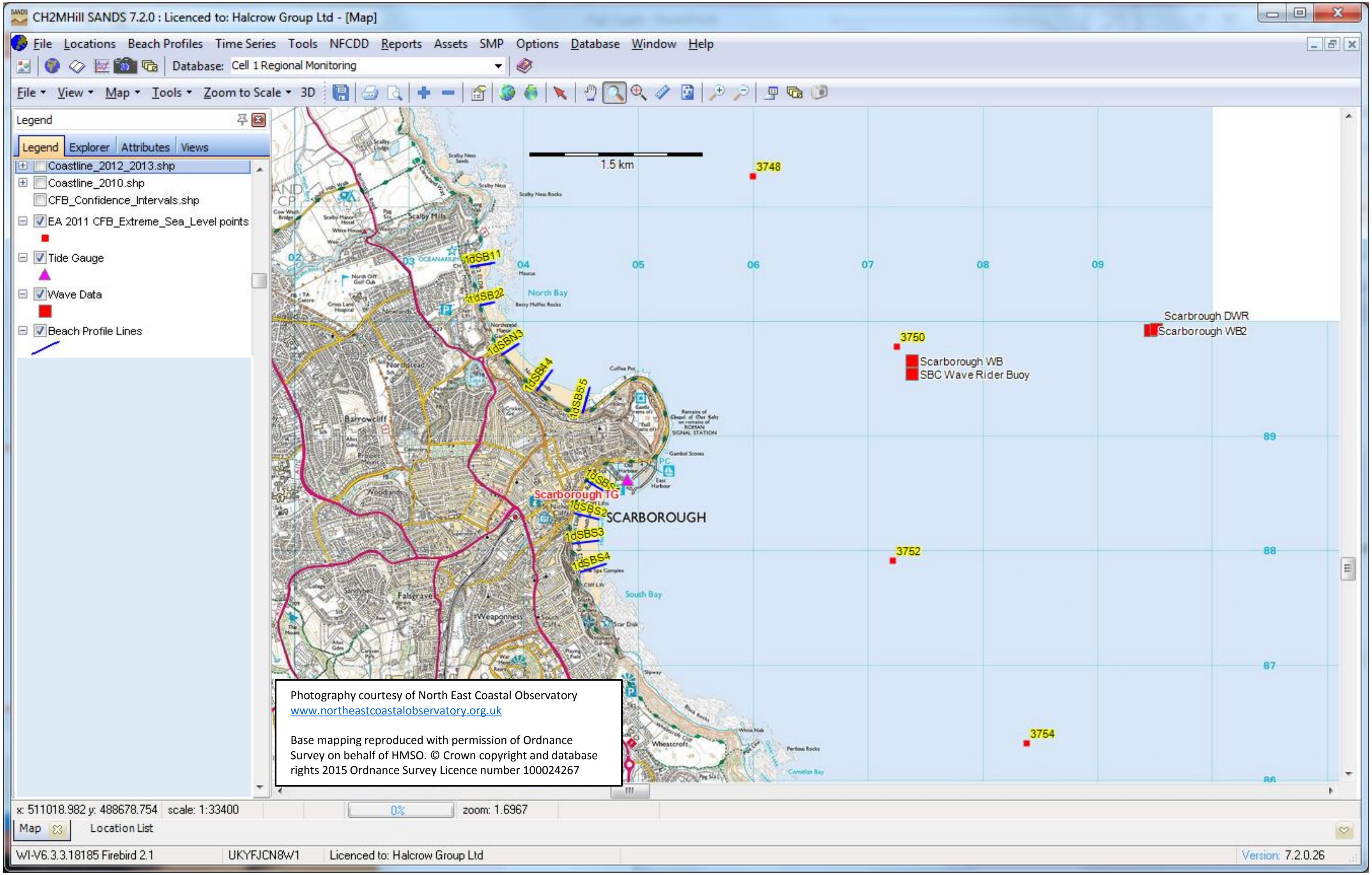
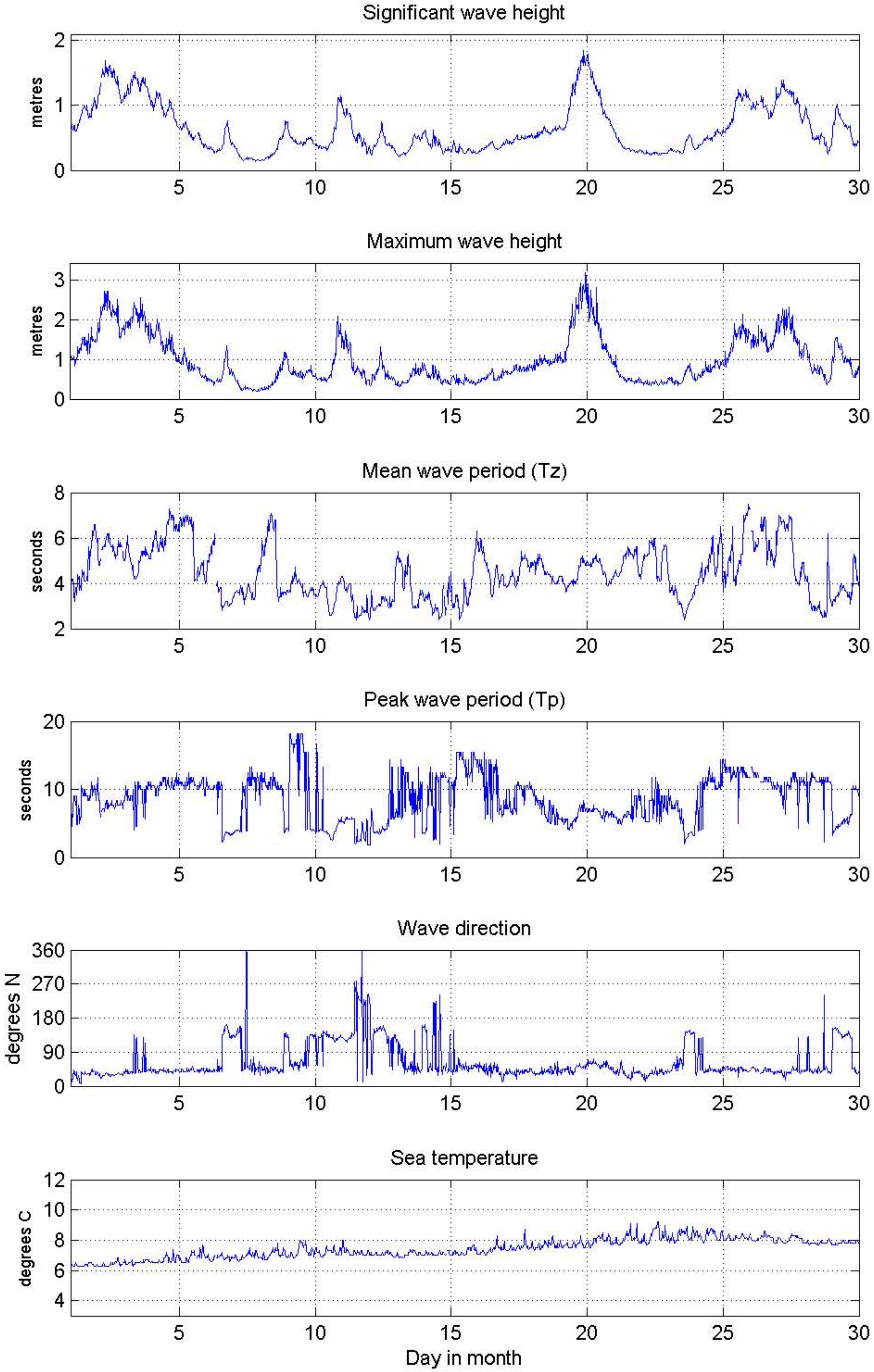


Figure A4 Locations of Scarborough wave buoys and tide gauge

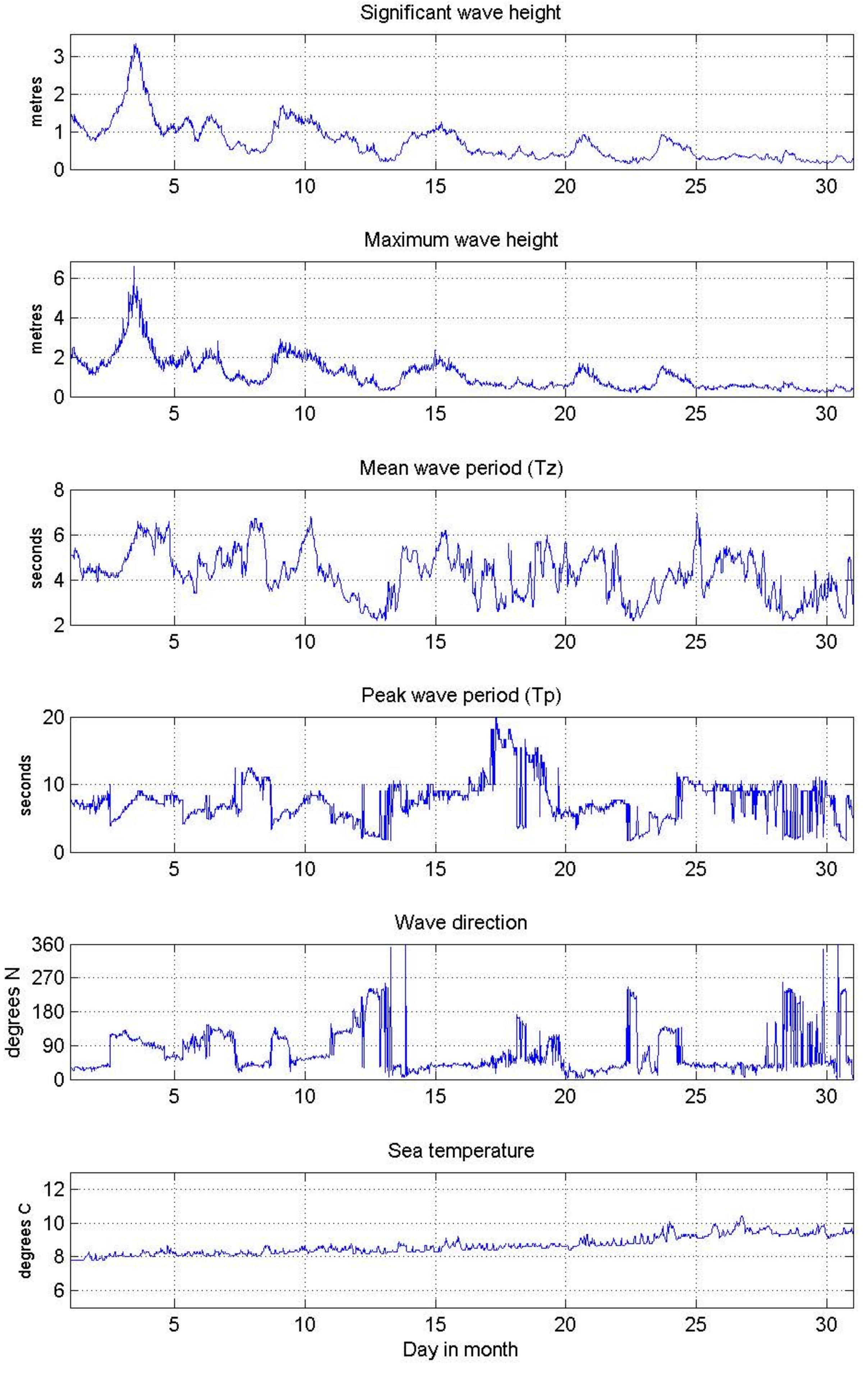
Appendix B

Supporting Graphs: Newbiggin Wave Buoy

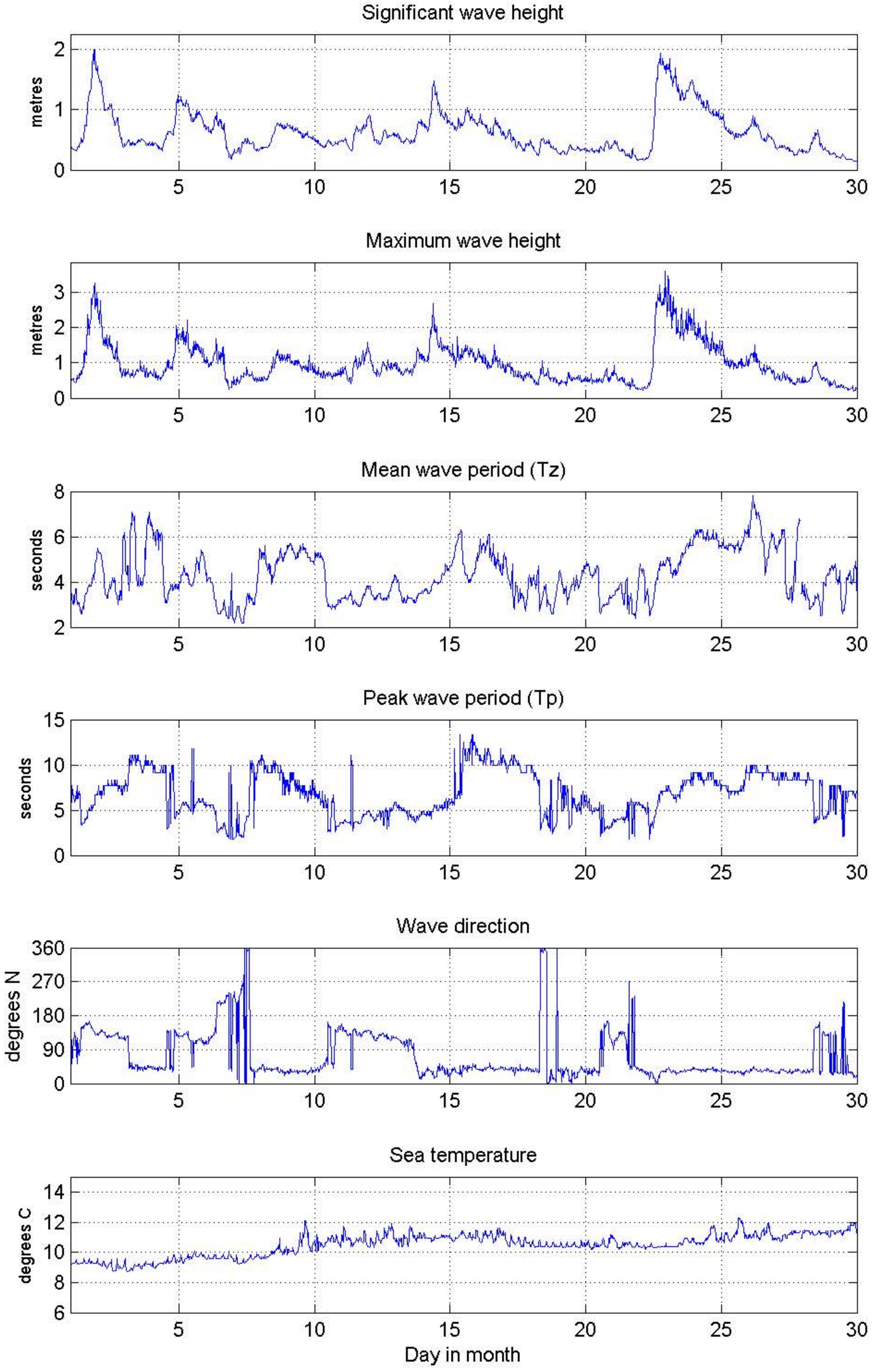
Newbiggin - April 2015



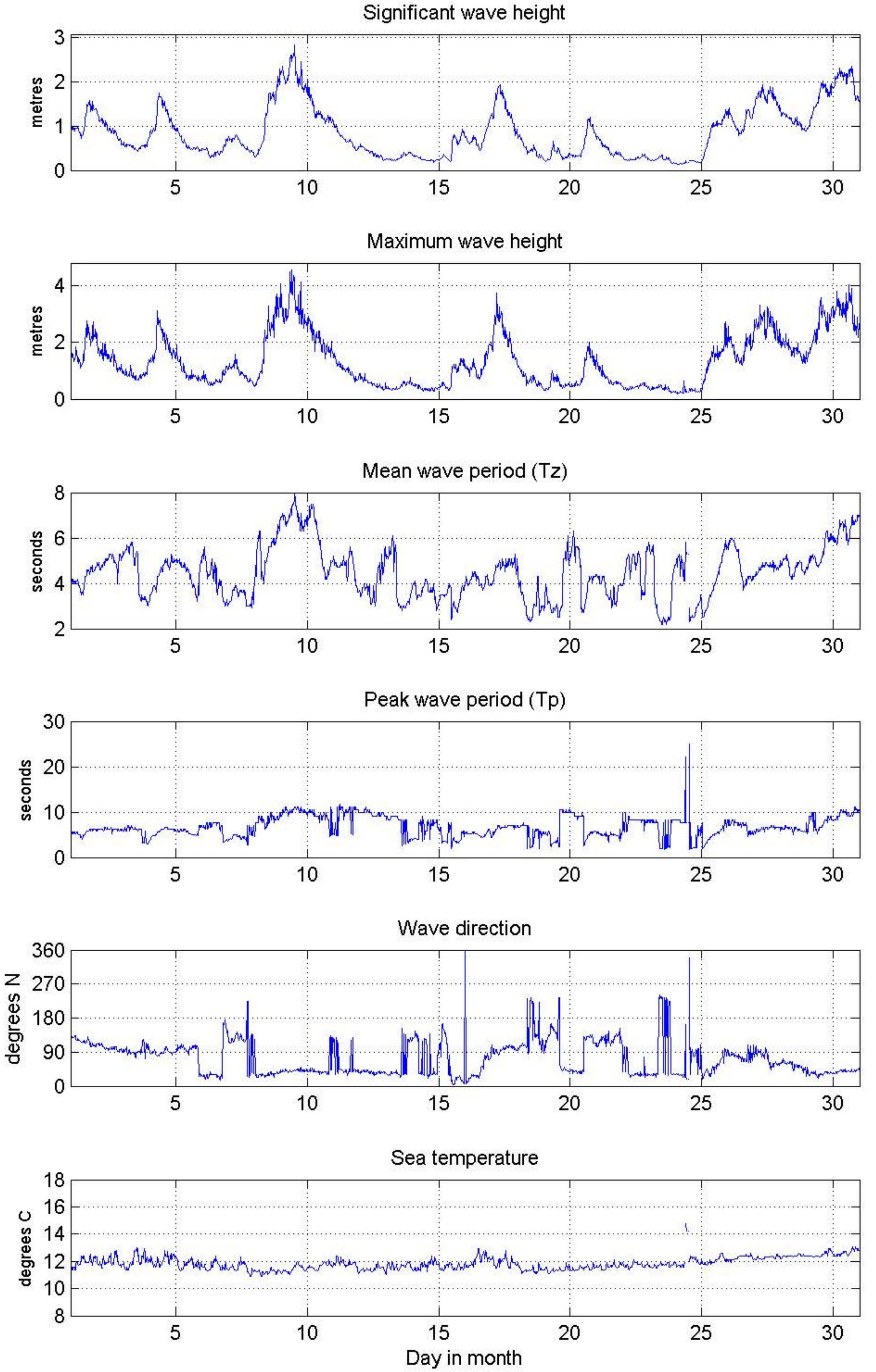
Newbiggin - May 2015



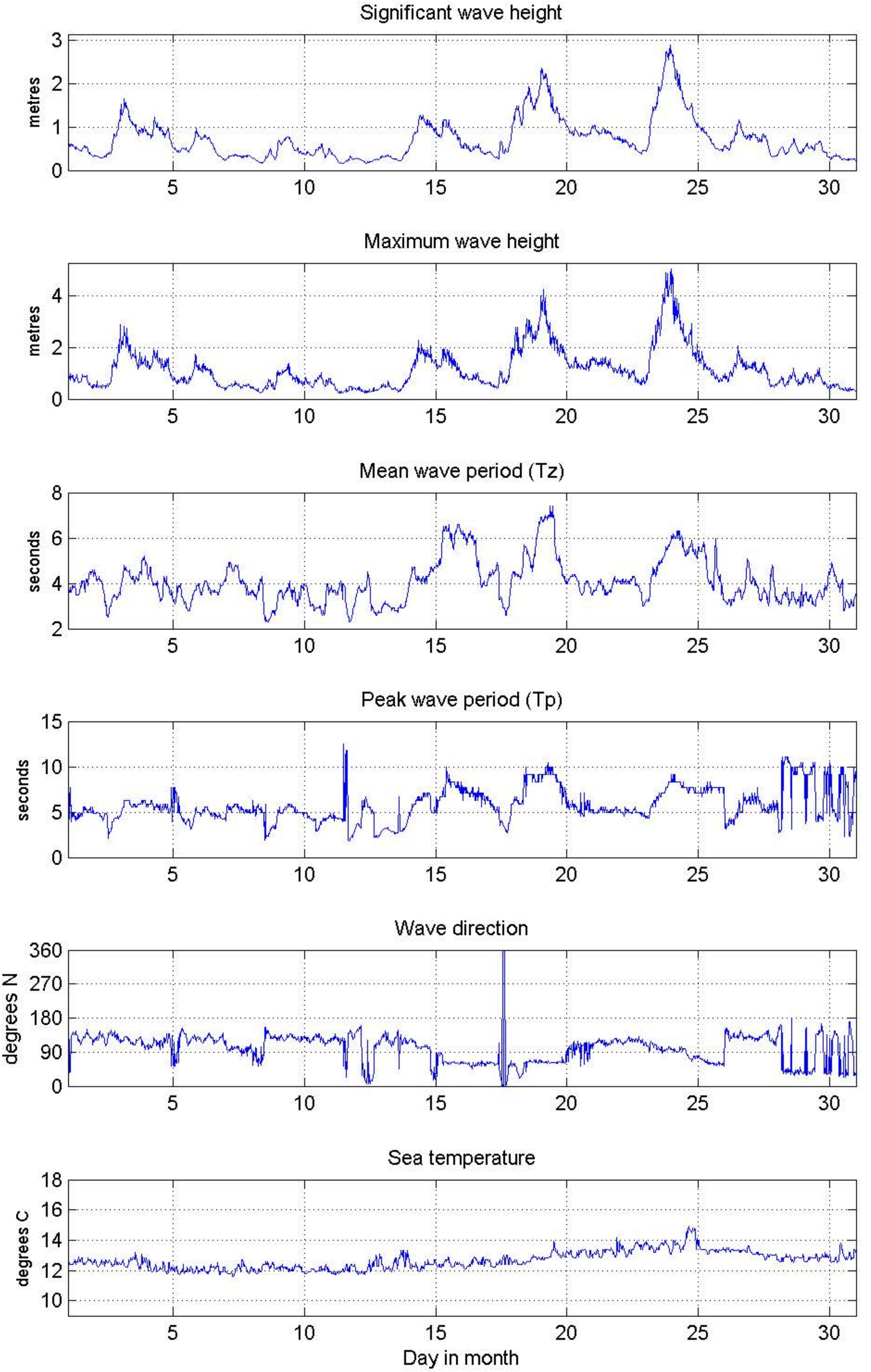
Newbiggin - June 2015



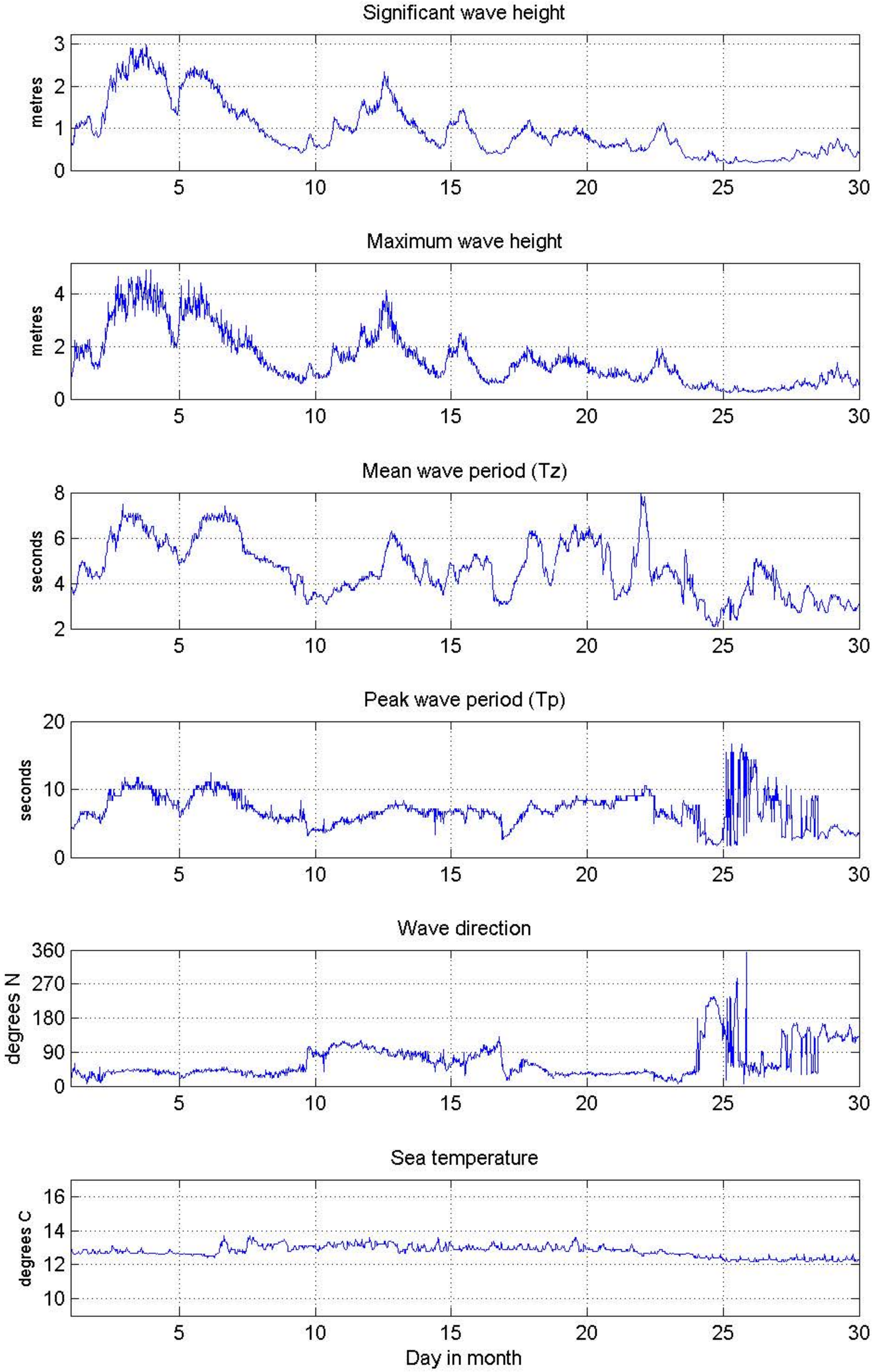
Newbiggin - July 2015



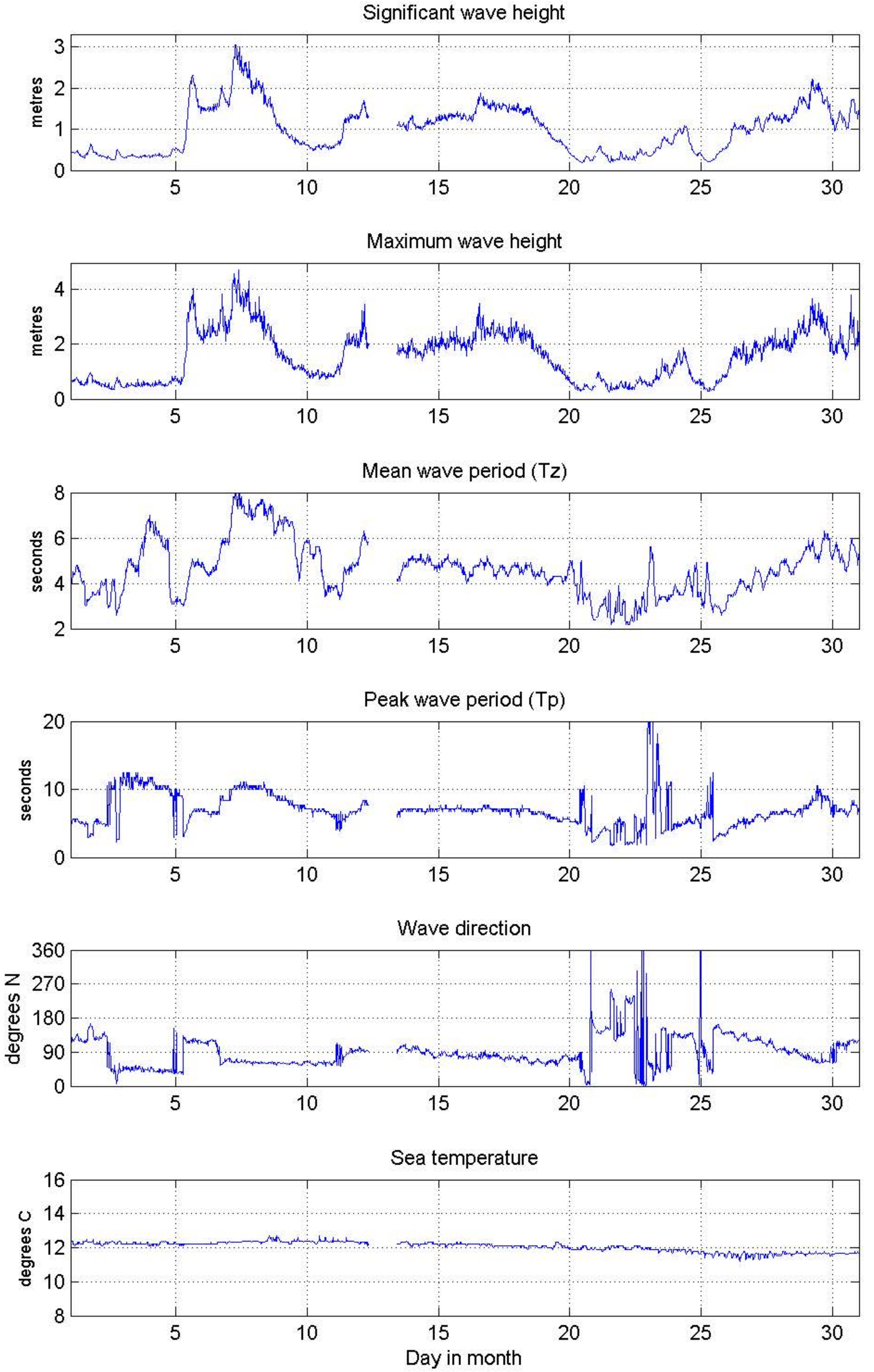
Newbiggin - August 2015



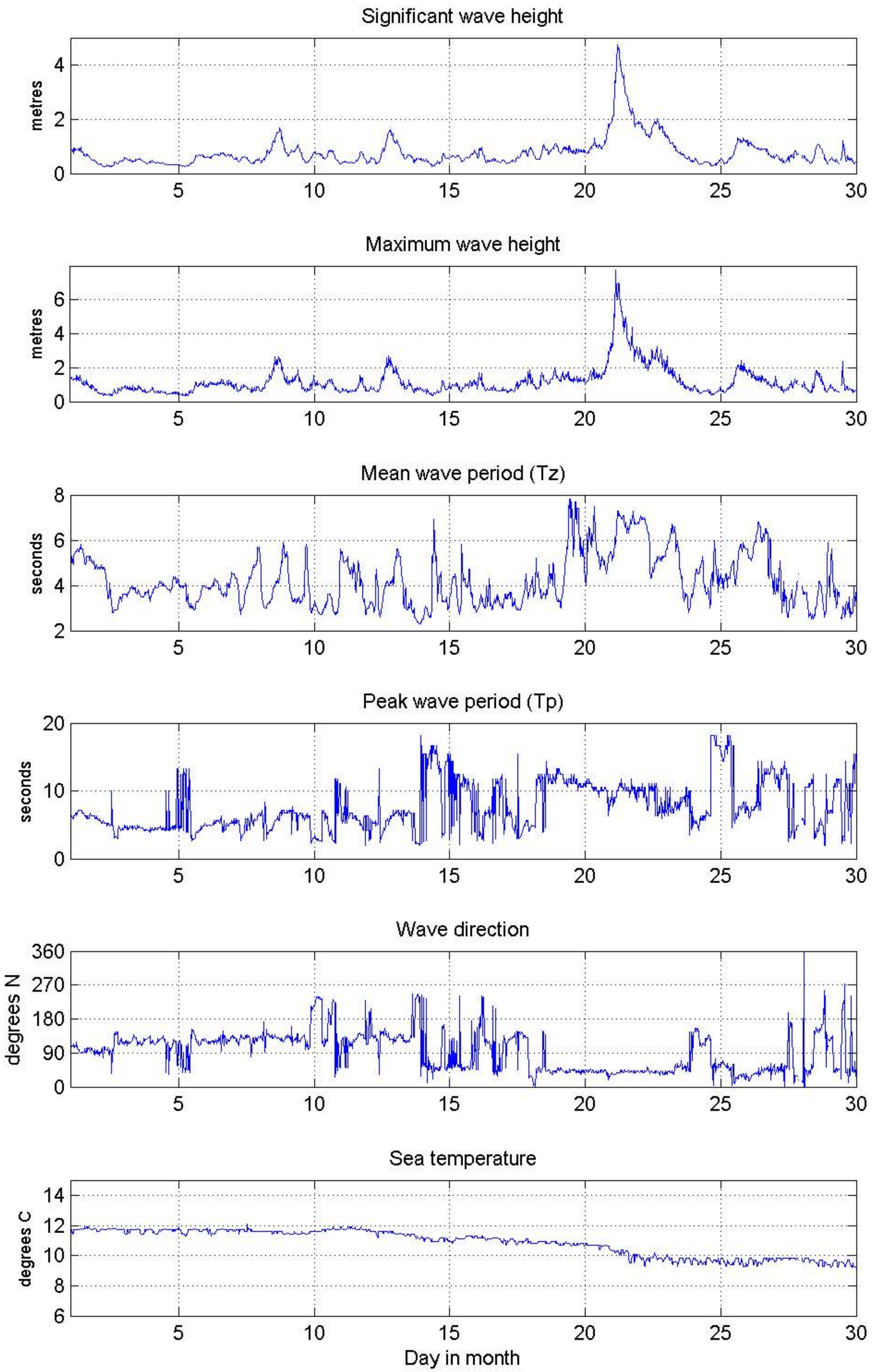
Newbiggin - September 2015



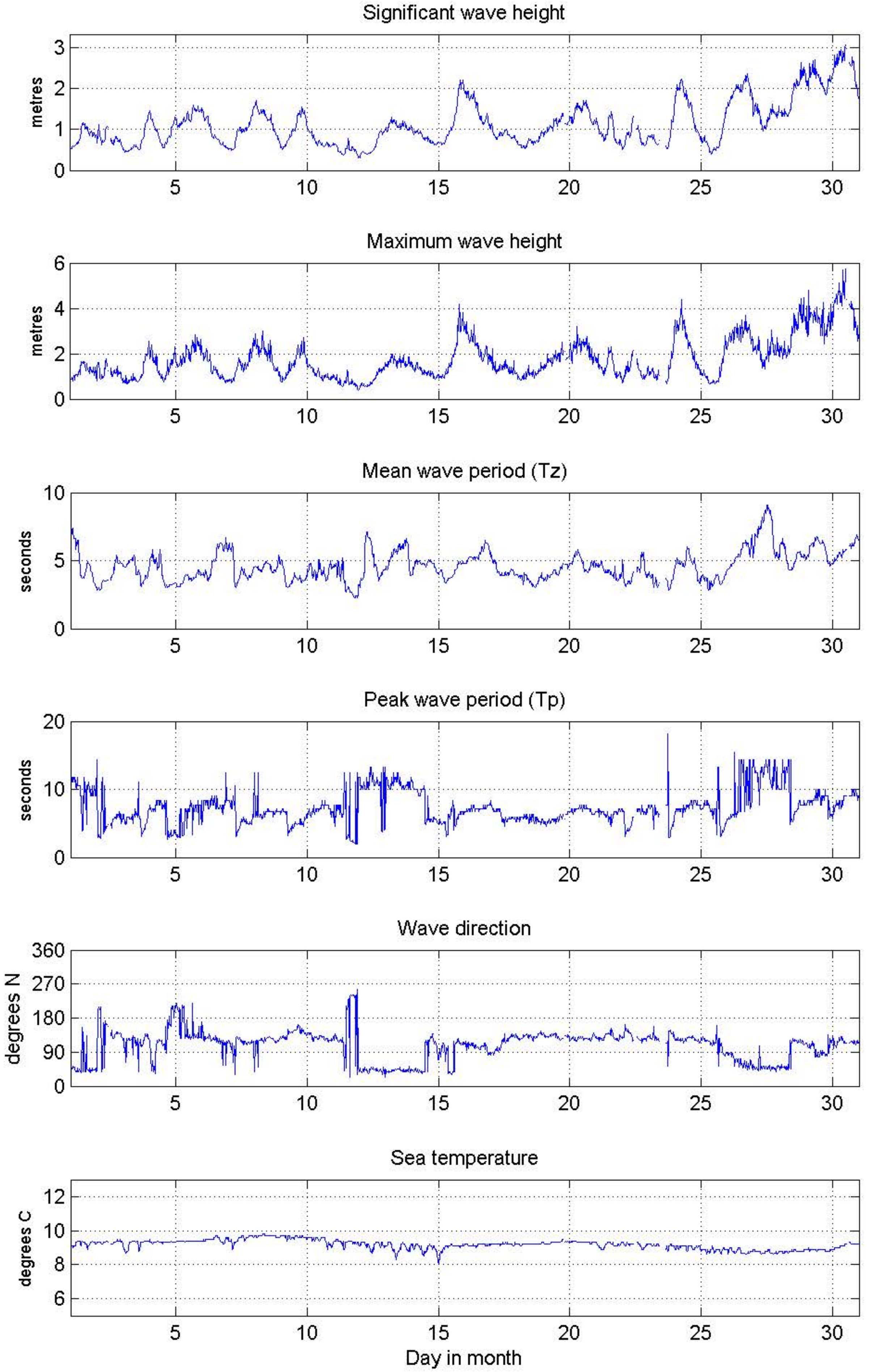
Newbiggin - October 2015



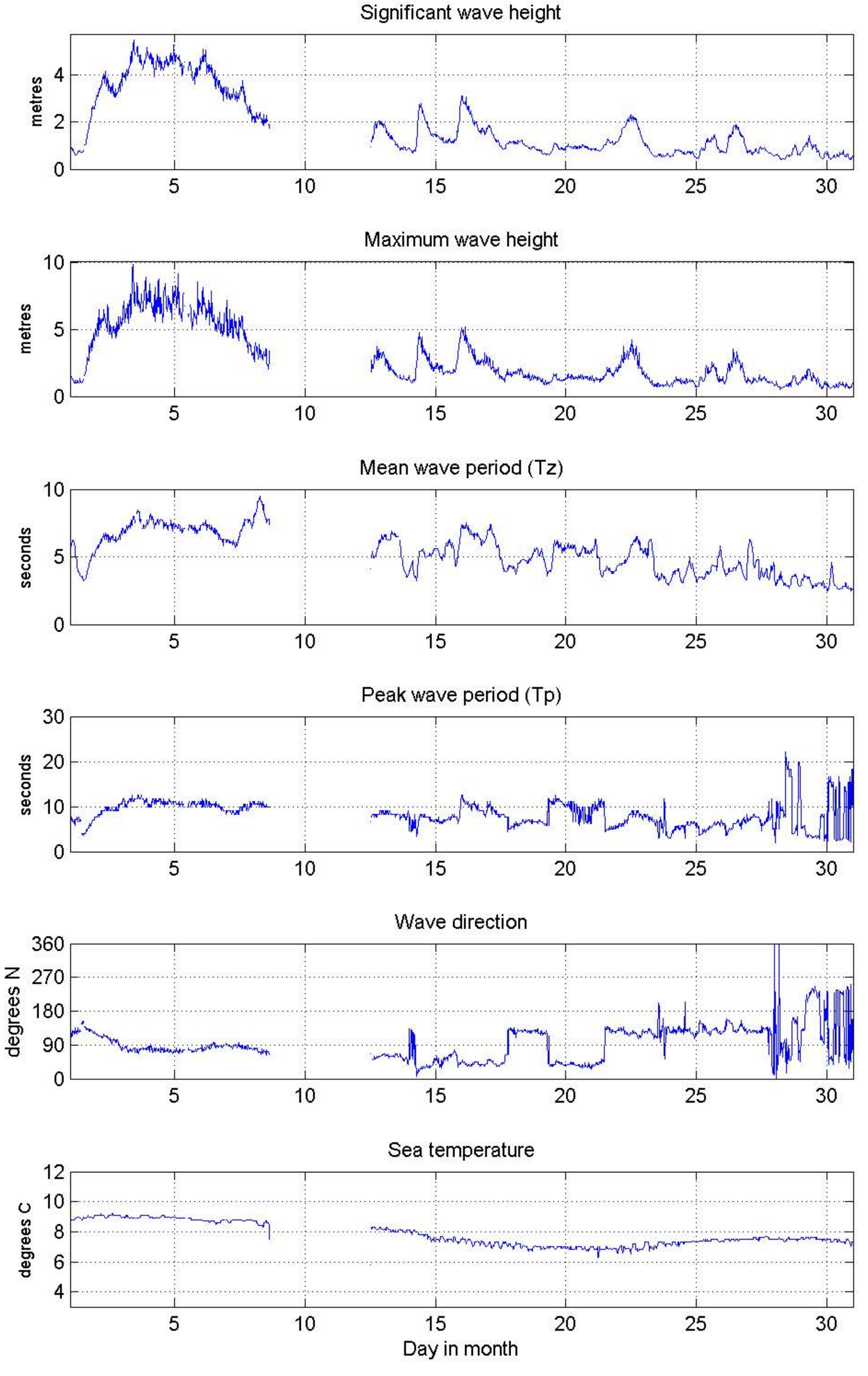
Newbiggin - November 2015



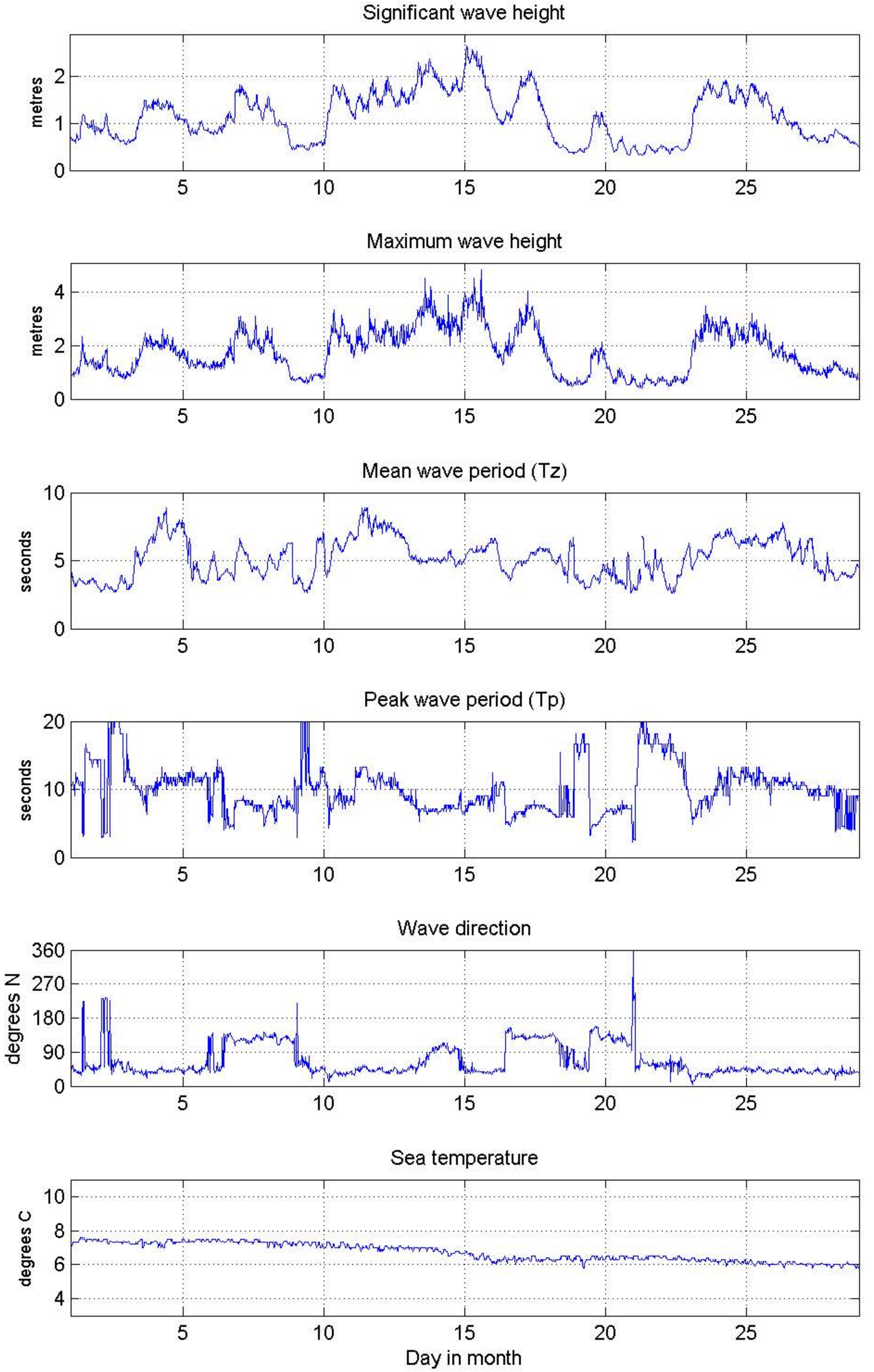
Newbiggin - December 2015



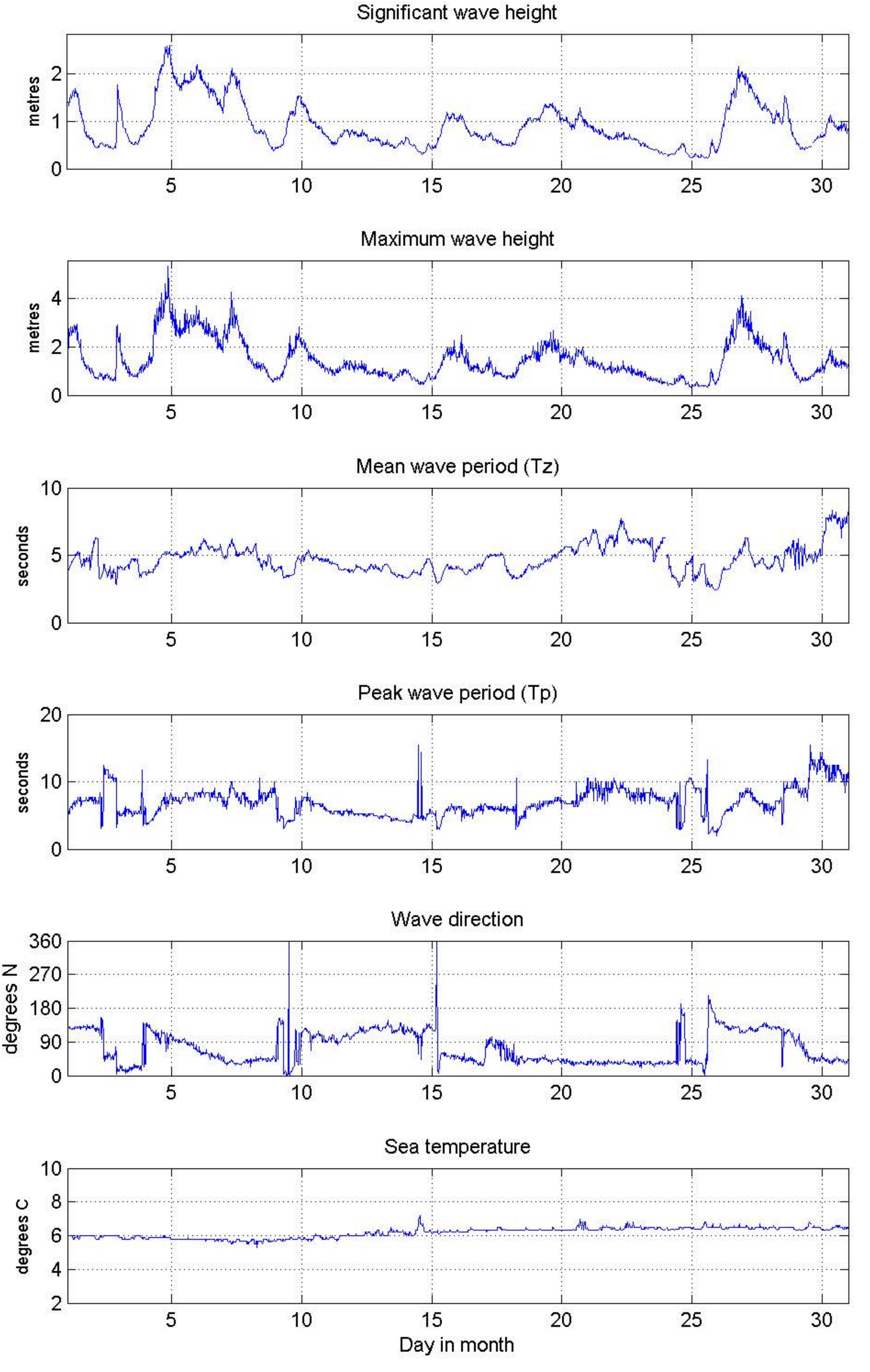
Newbiggin - January 2016



Newbiggin - February 2016



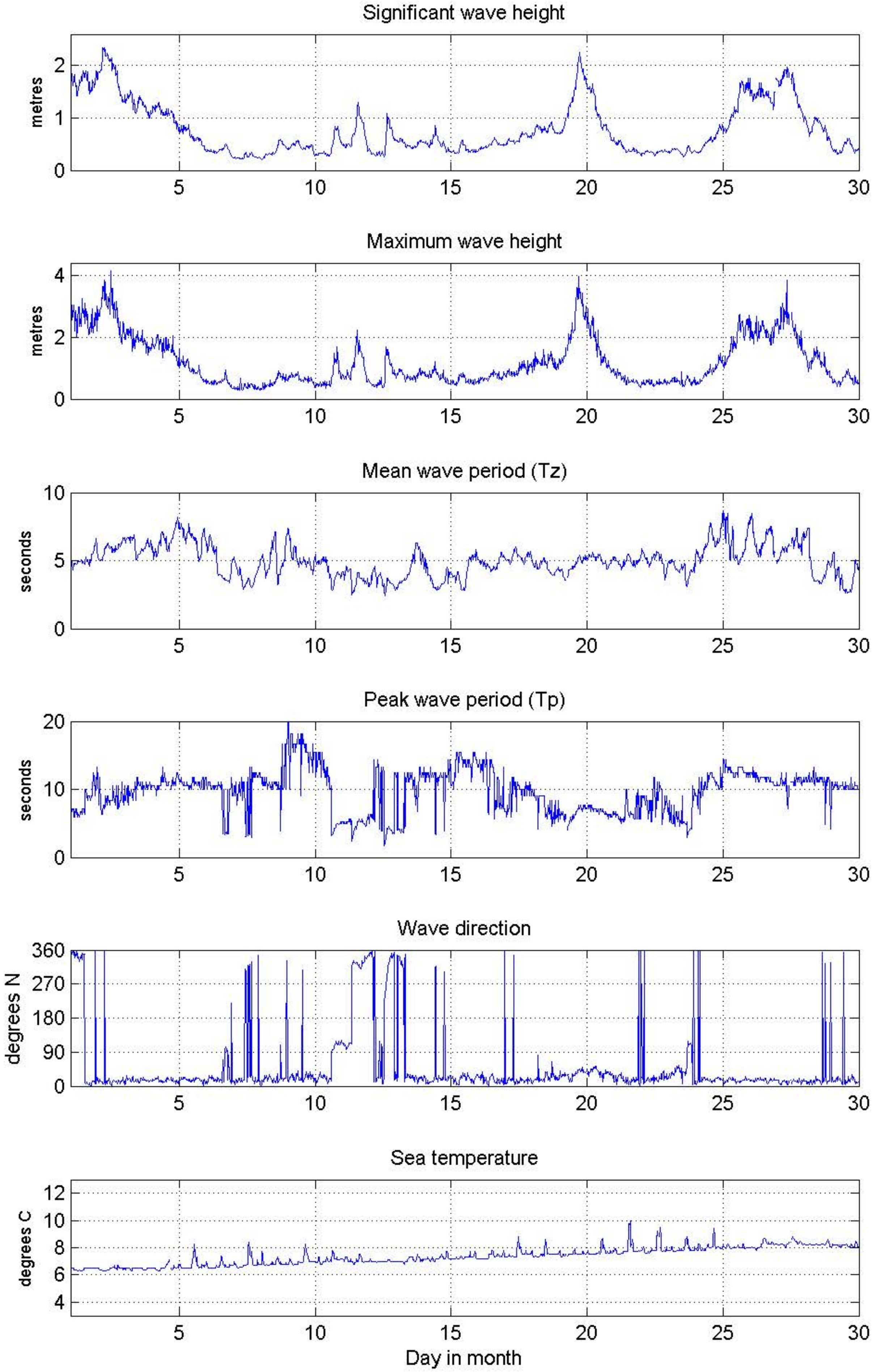
Newbiggin - March 2016



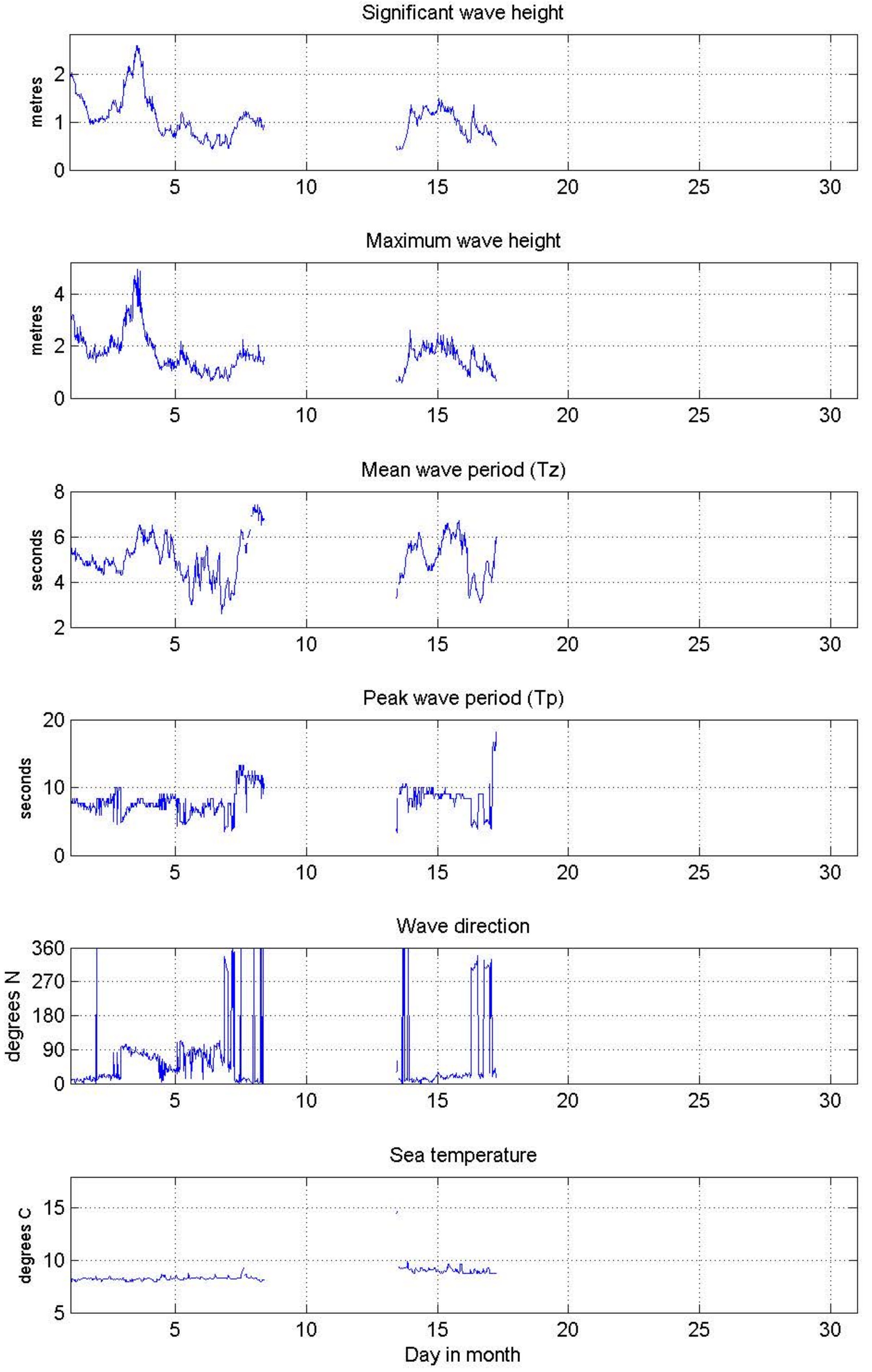
Appendix C

Supporting Graphs: Whitby Wave Buoy

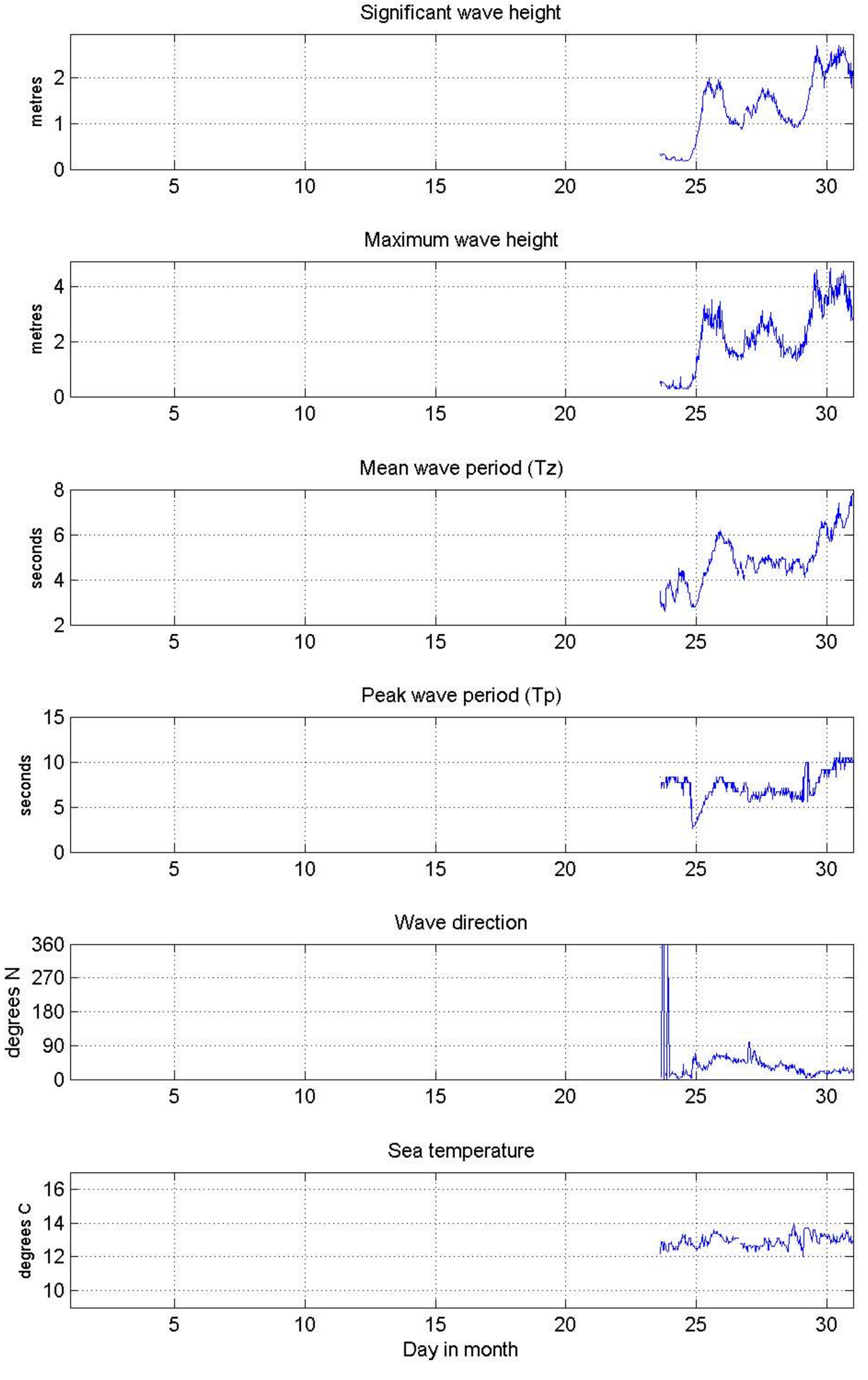
Whitby - April 2015



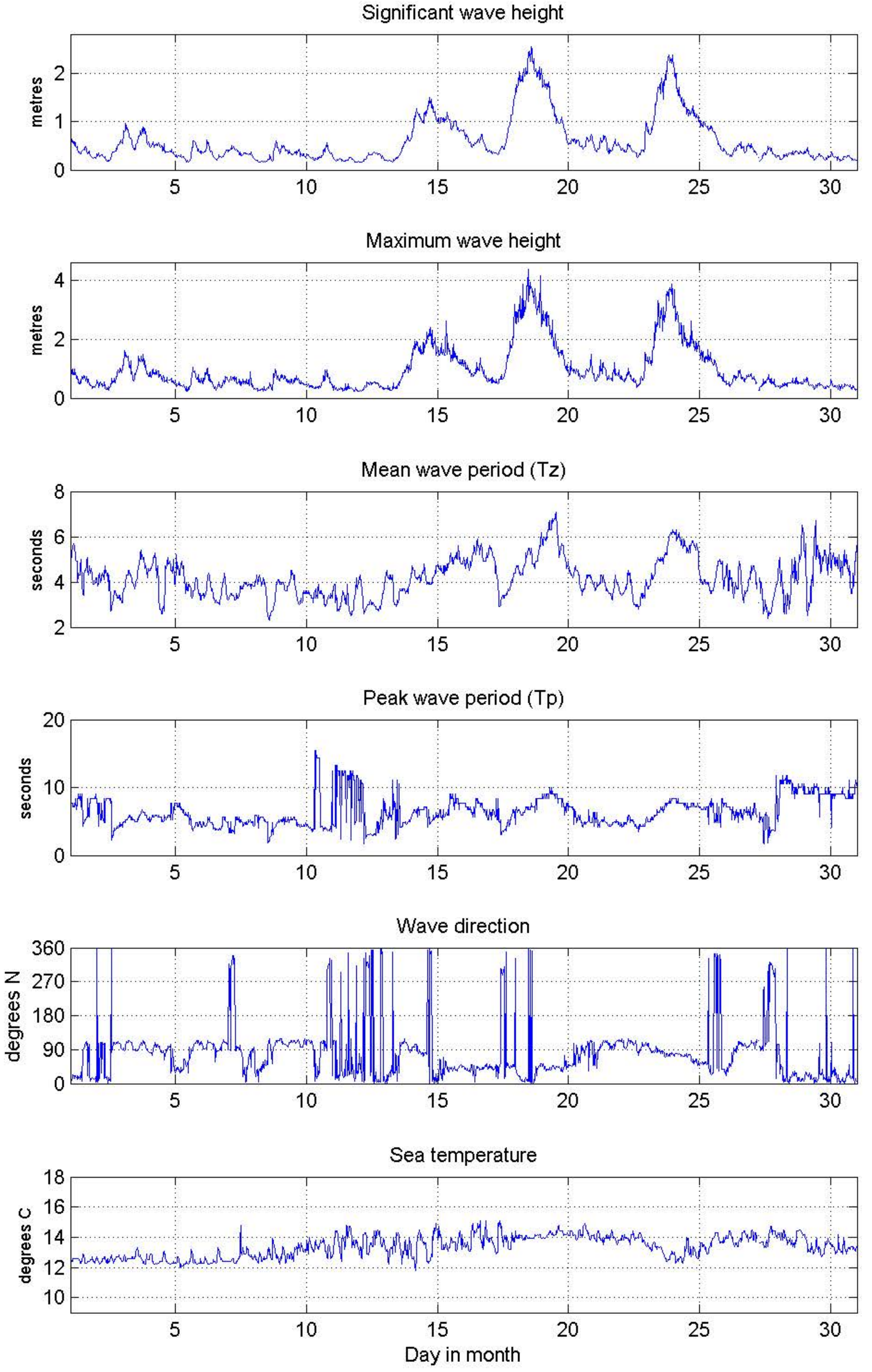
Whitby - May 2015



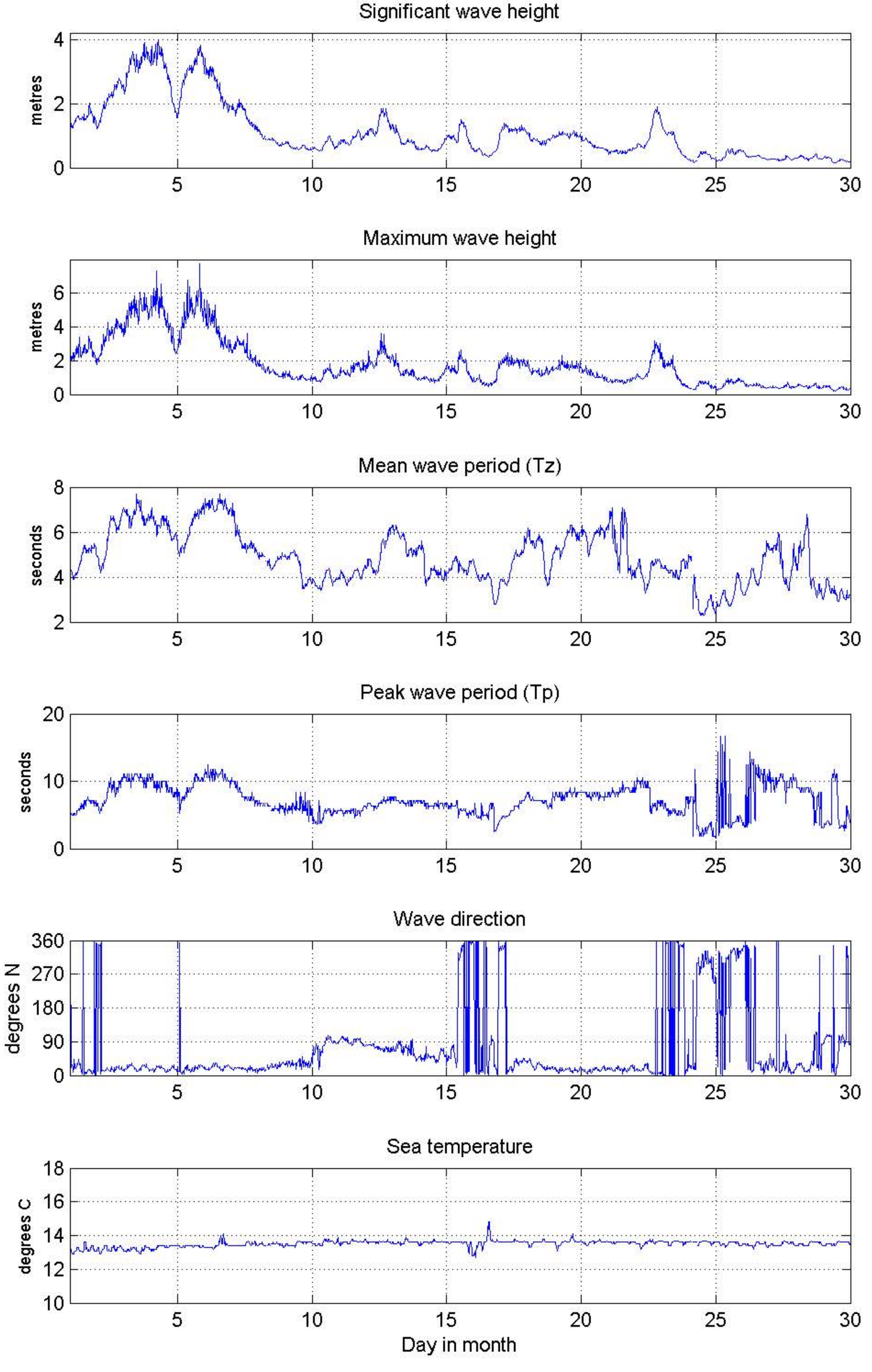
Whitby - July 2015



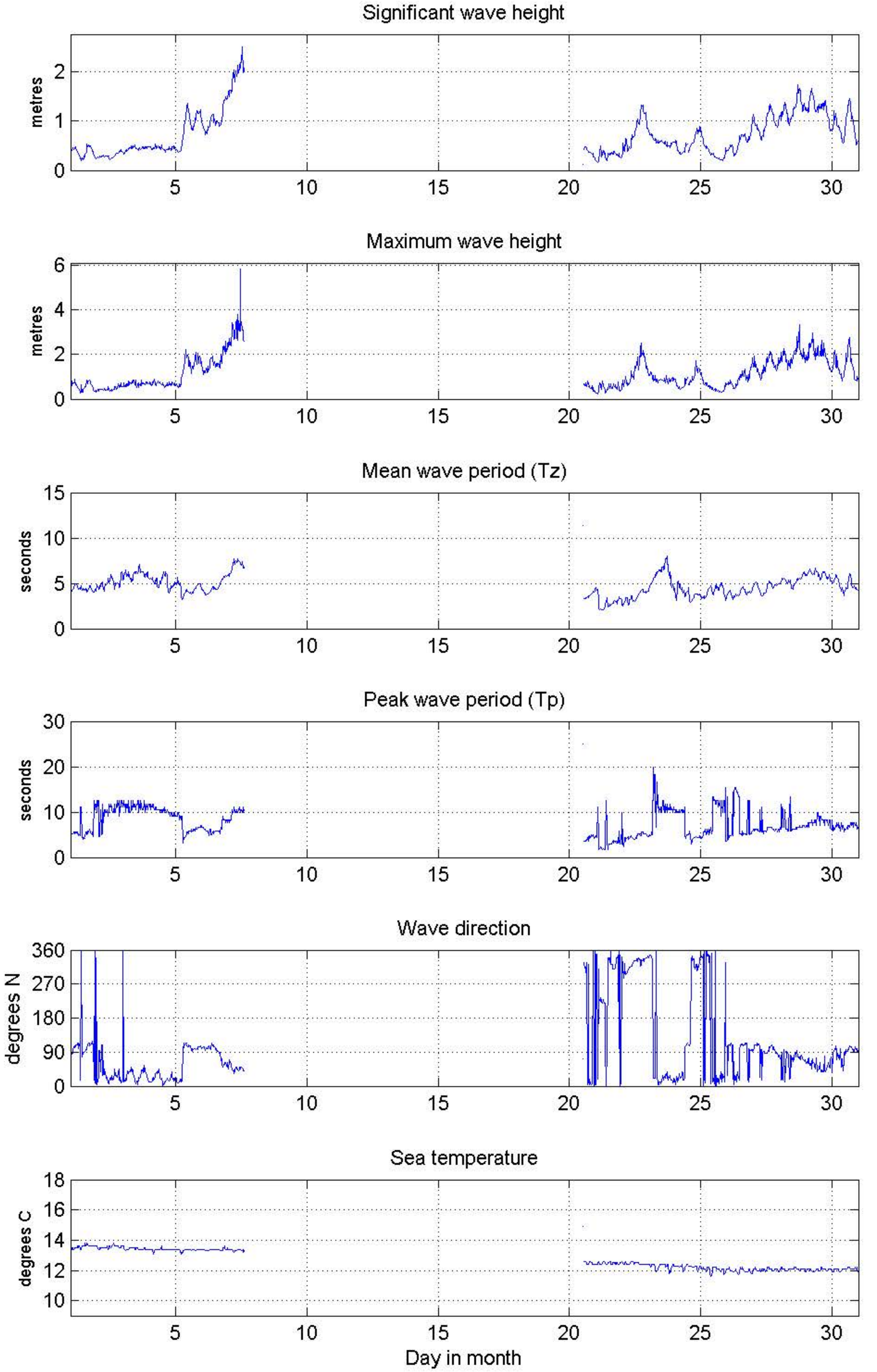
Whitby - August 2015



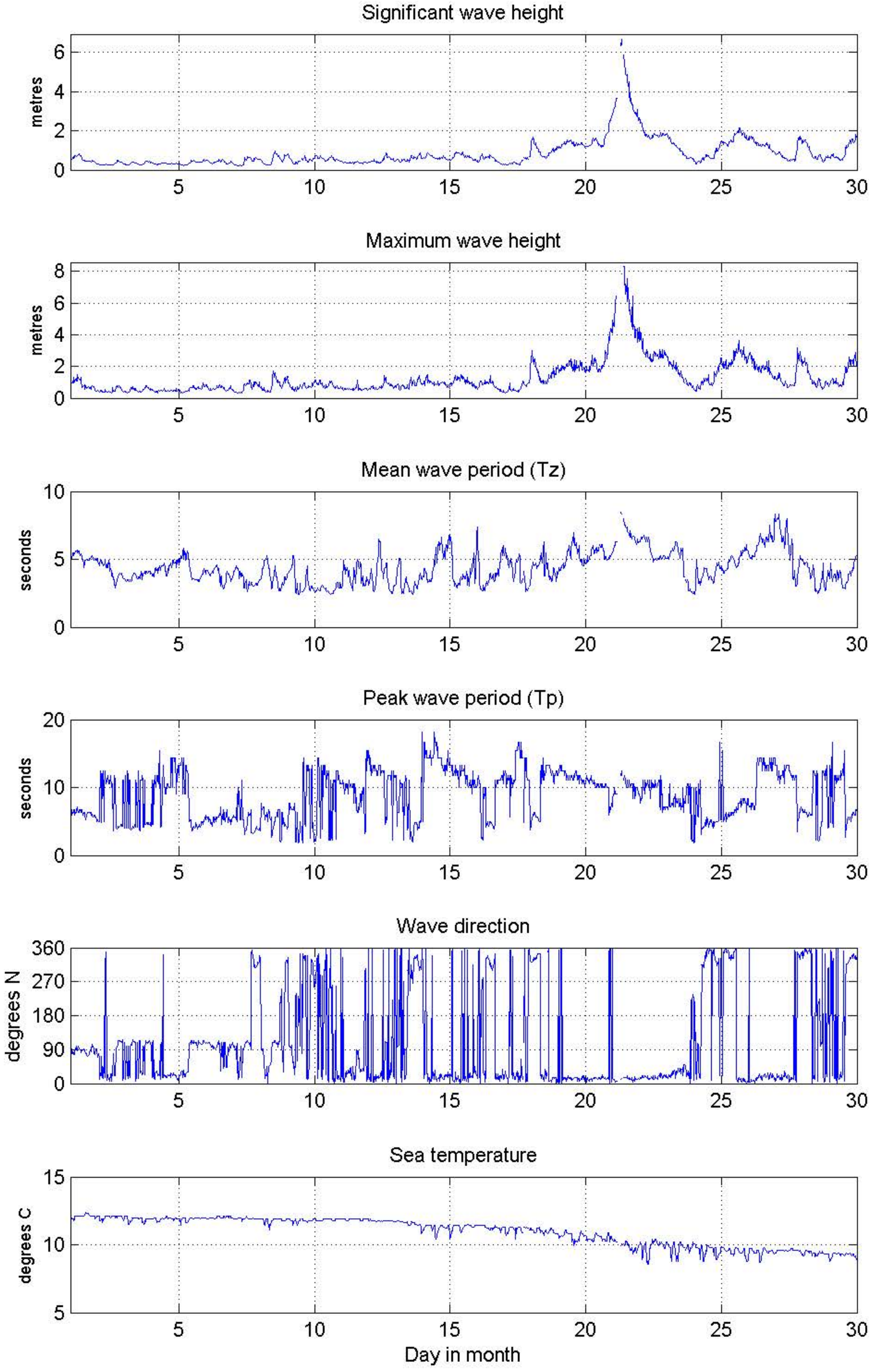
Whitby - September 2015



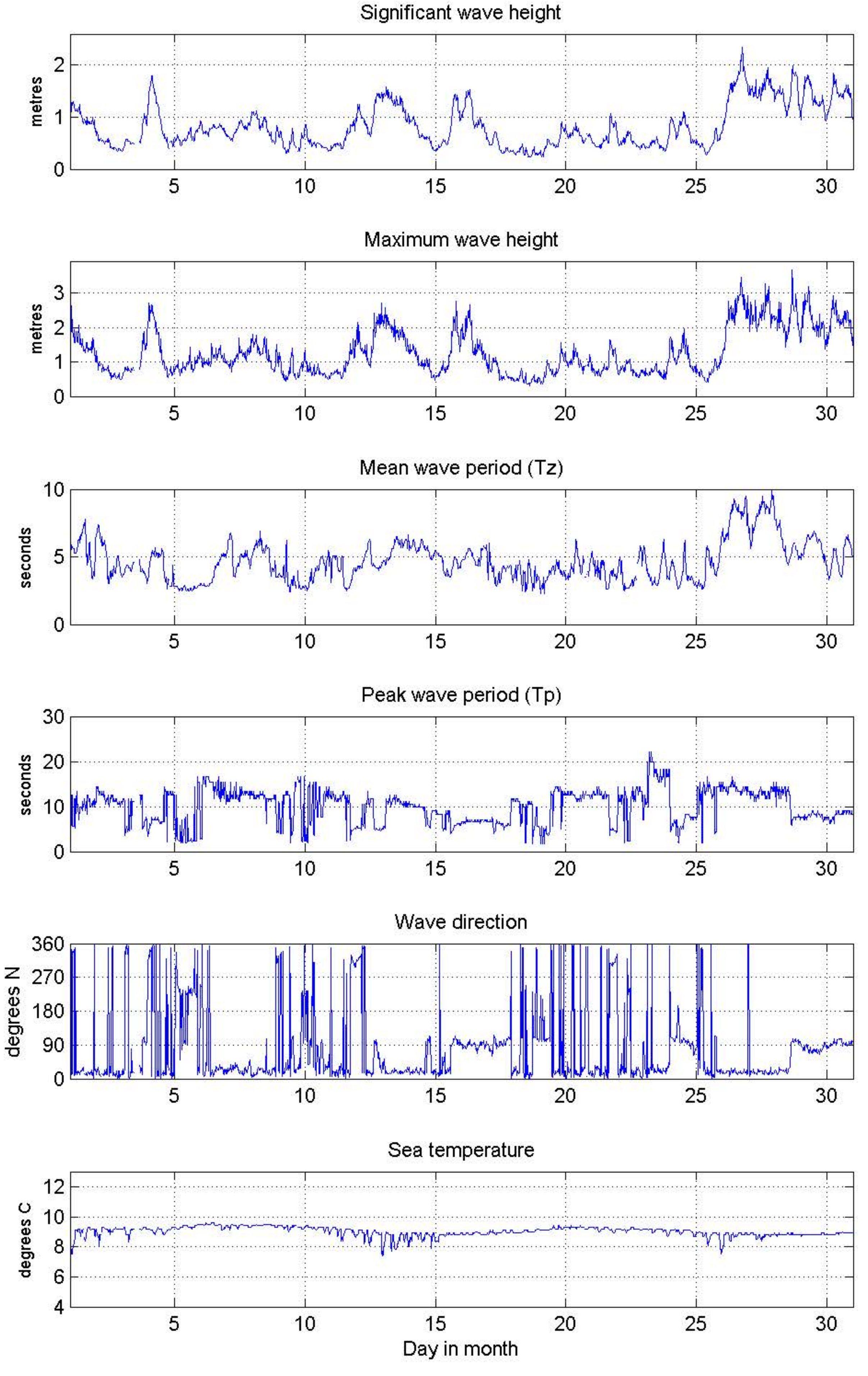
Whitby - October 2015



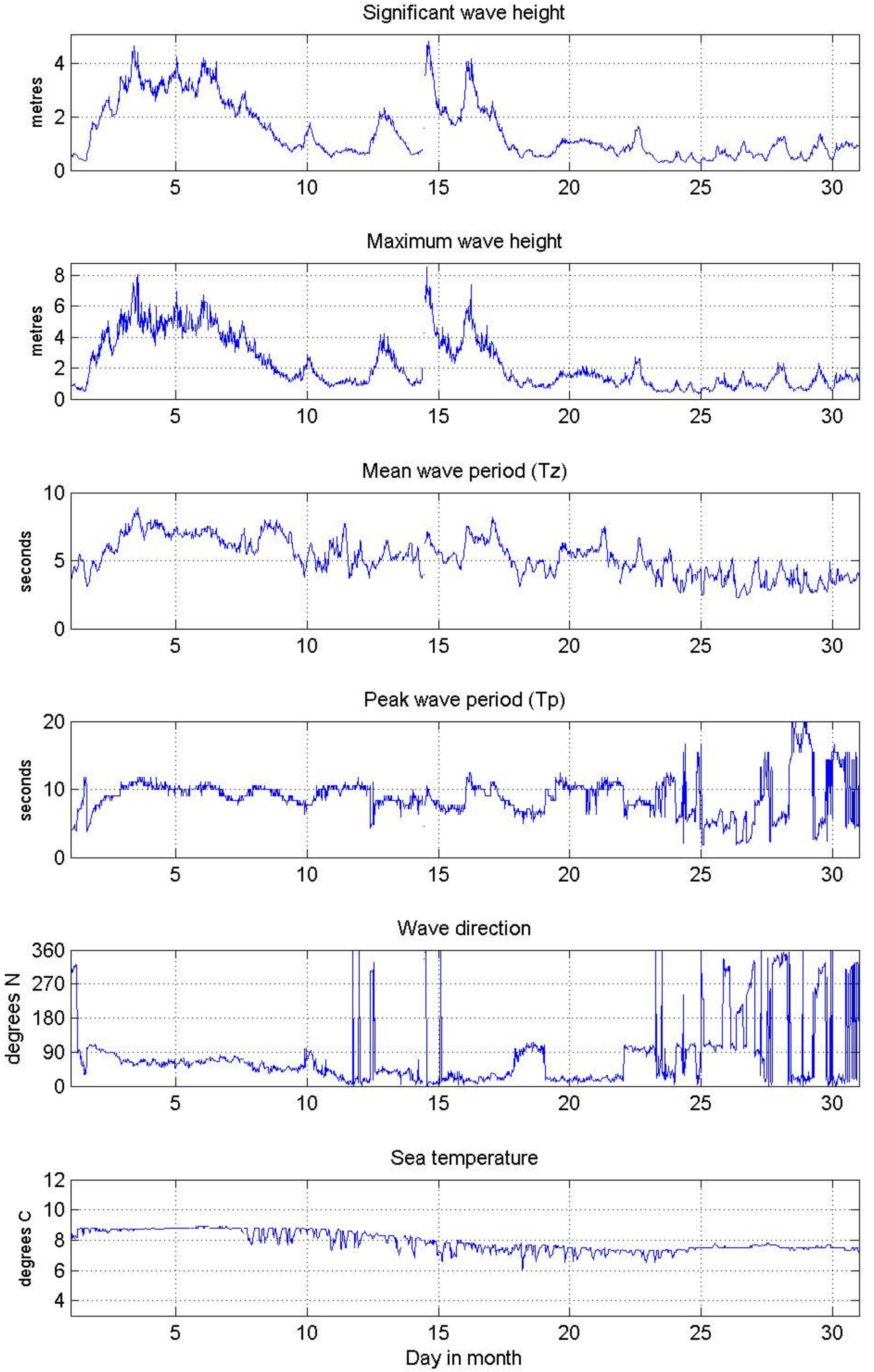
Whitby - November 2015



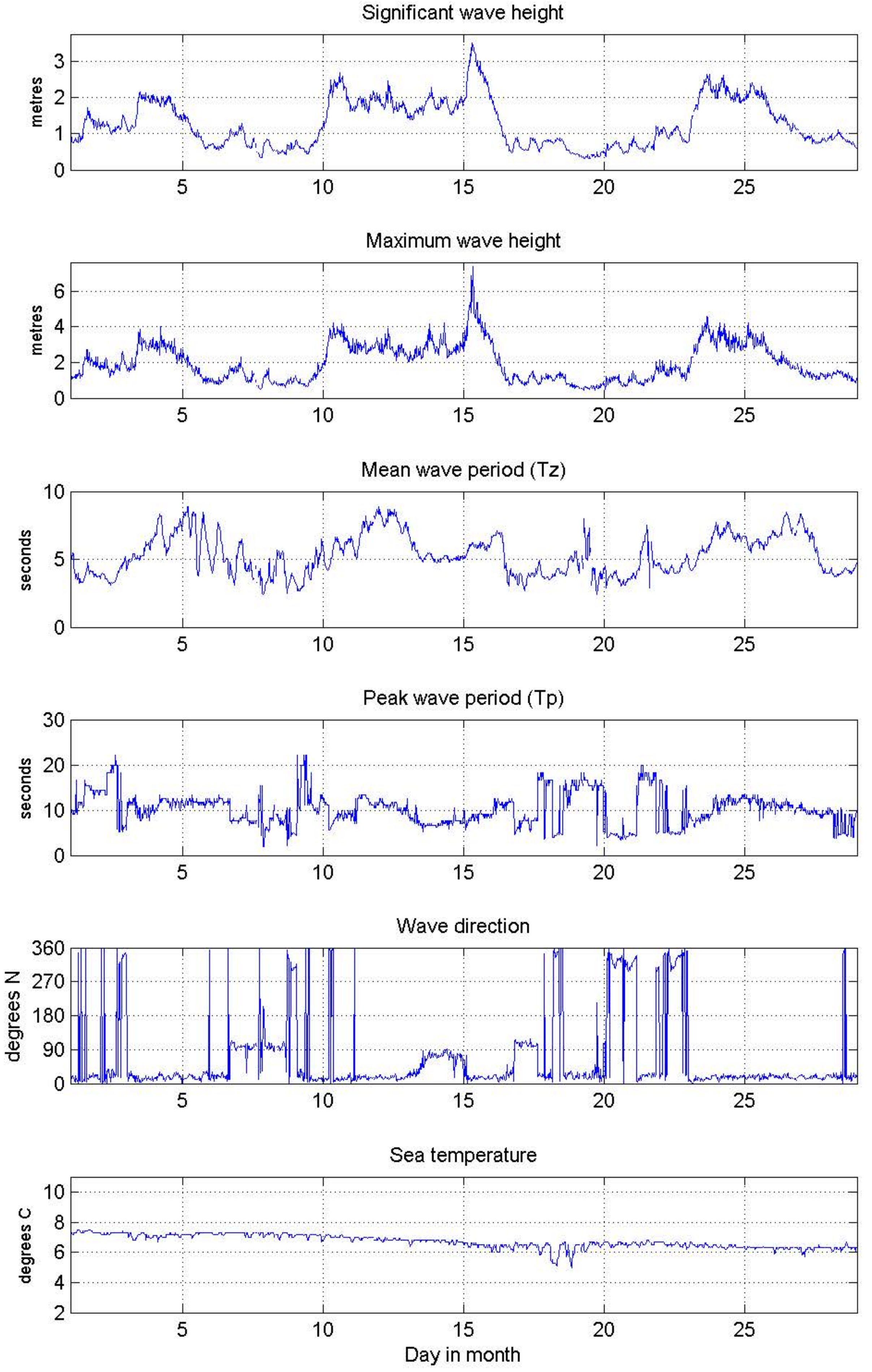
Whitby - December 2015



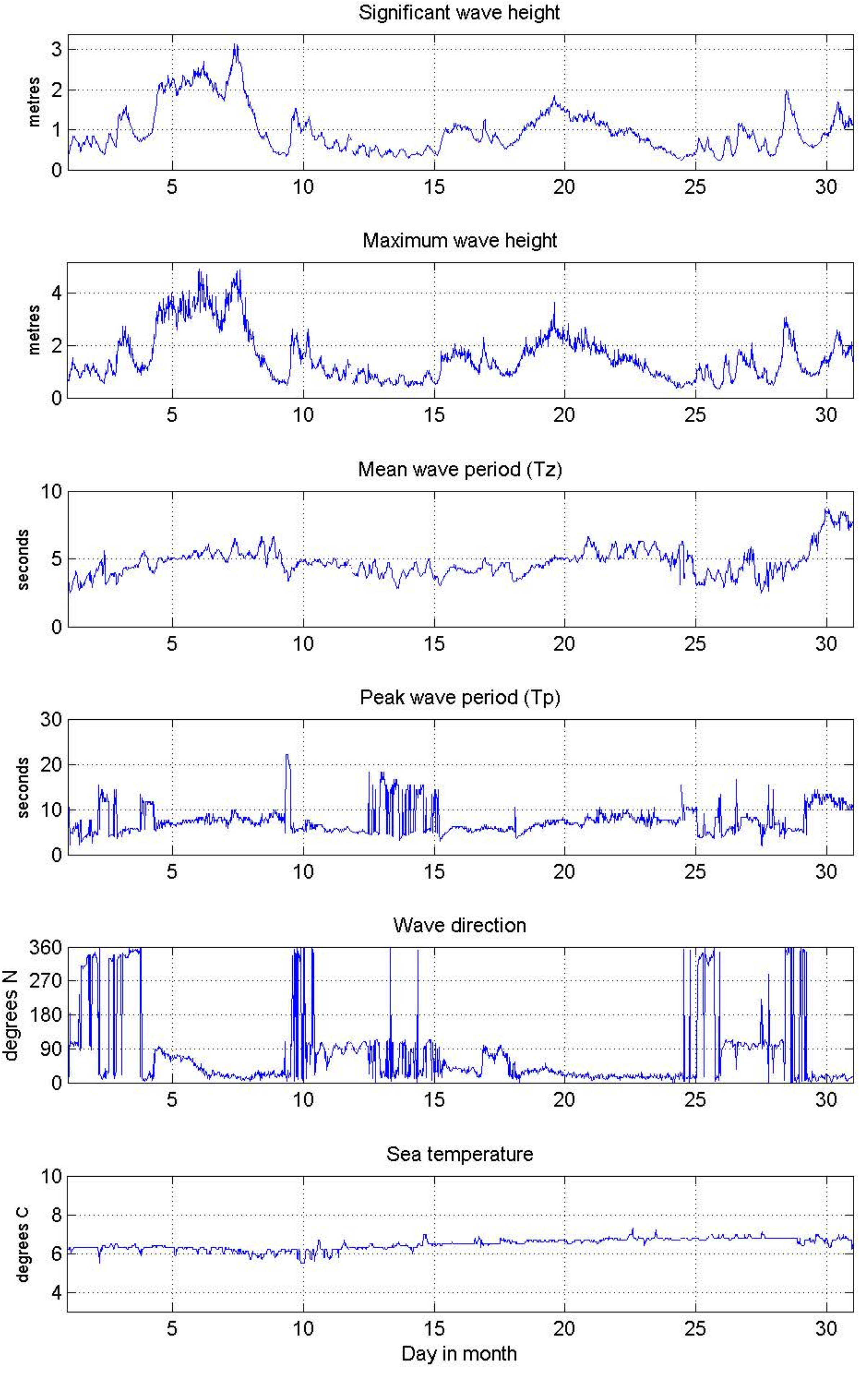
Whitby - January 2016



Whitby - February 2016



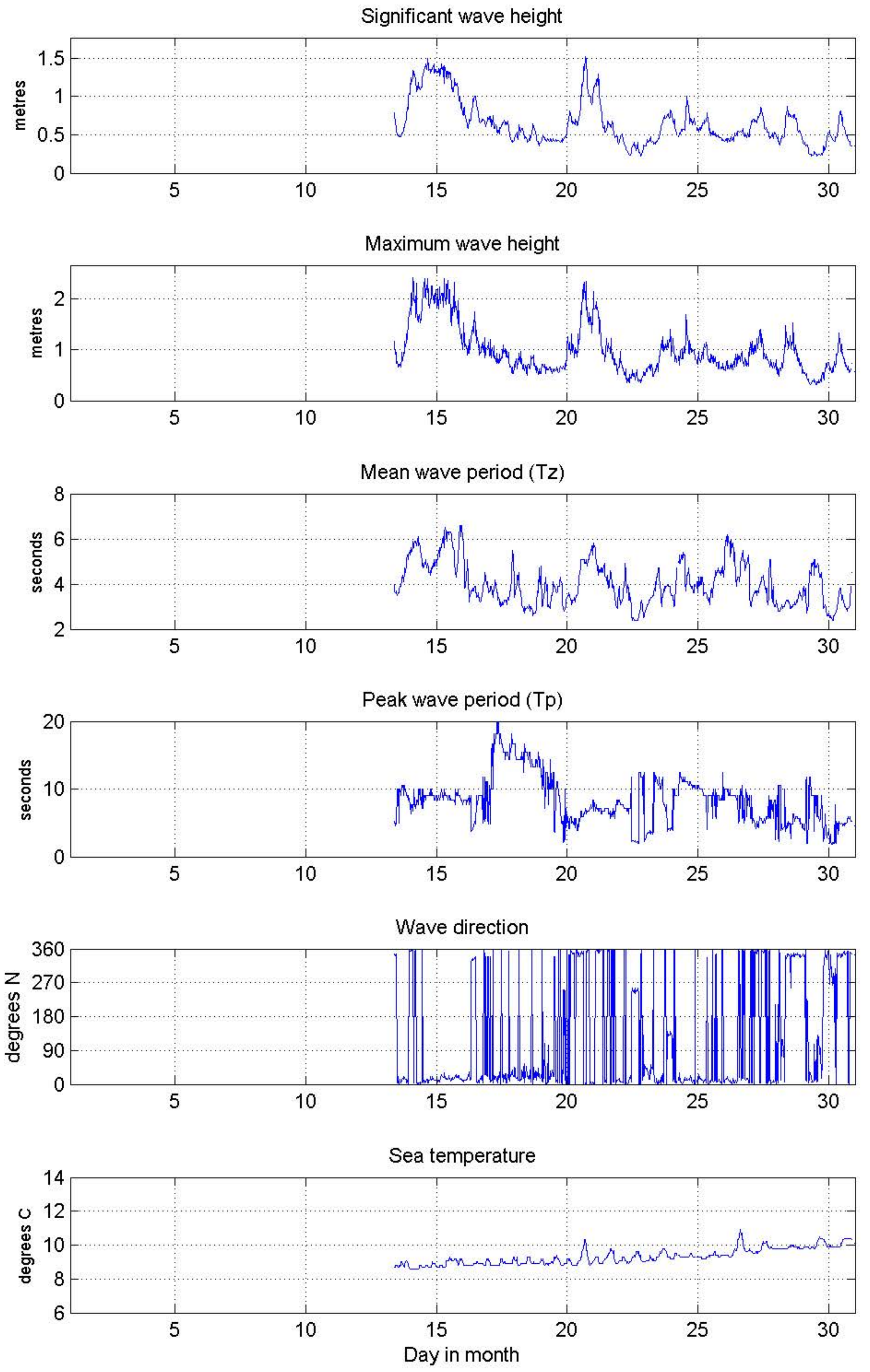
Whitby - March 2016



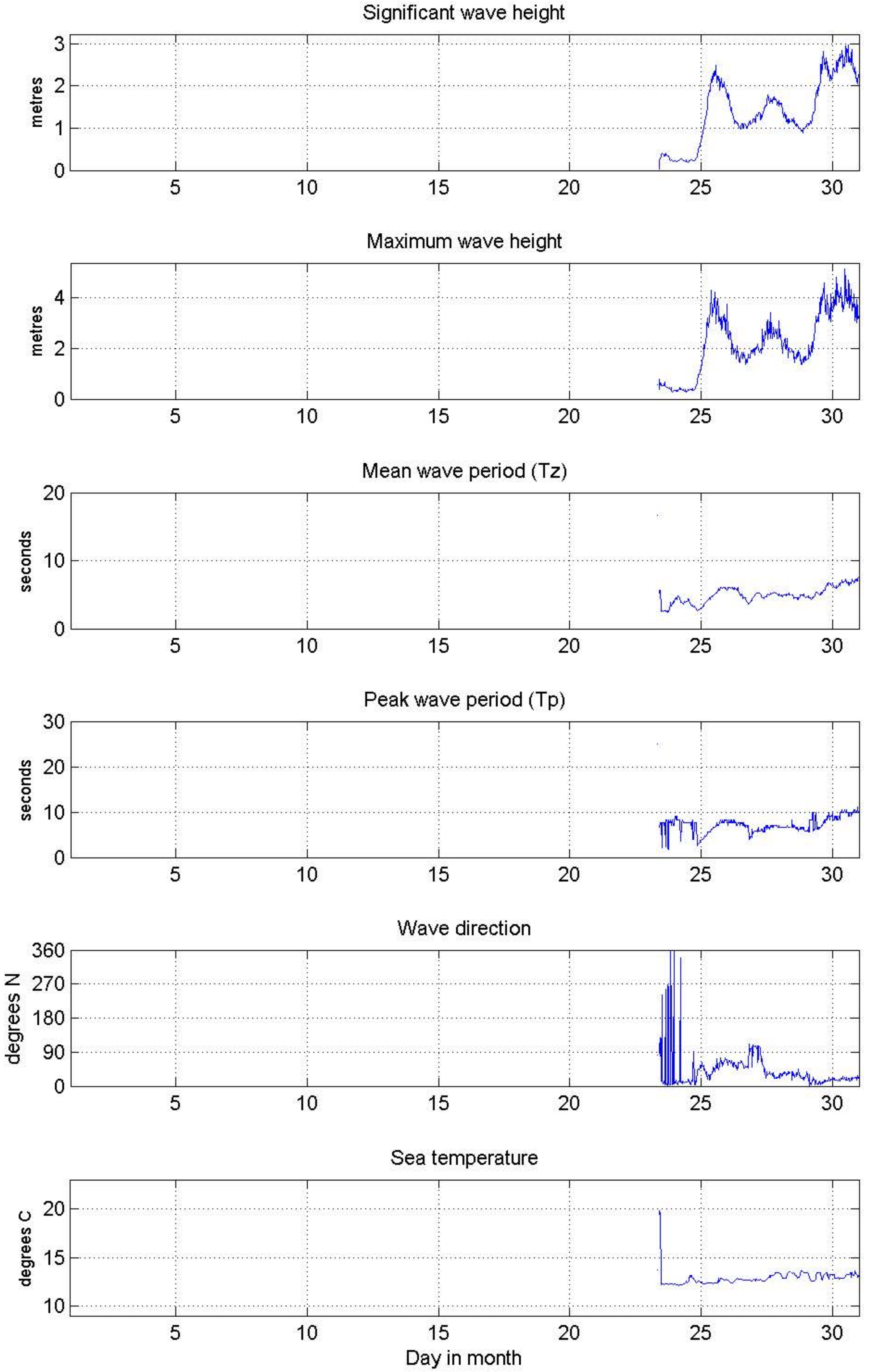
Appendix D

Supporting Graphs: Scarborough Wave Buoy

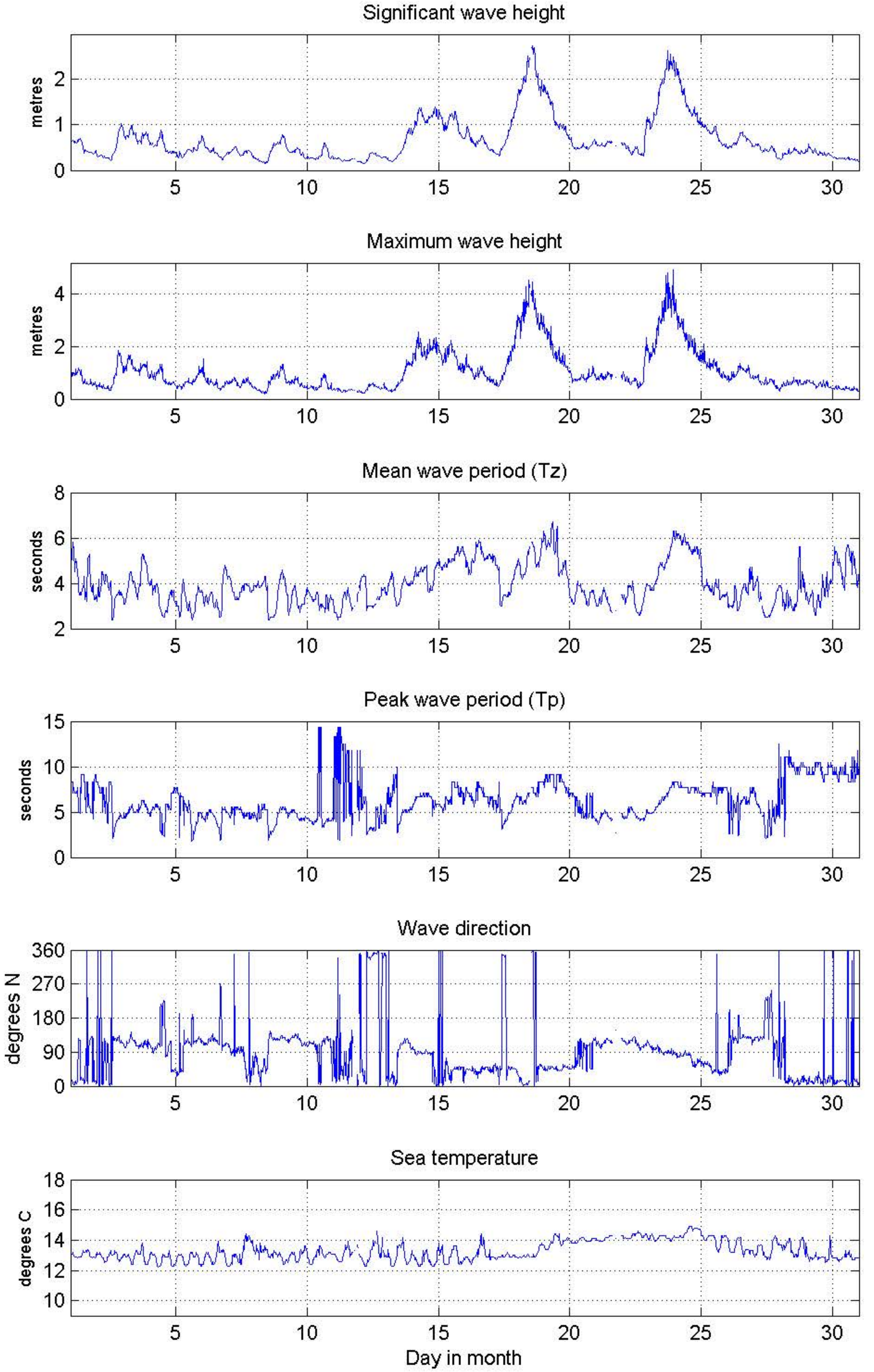
Scarborough - May 2015



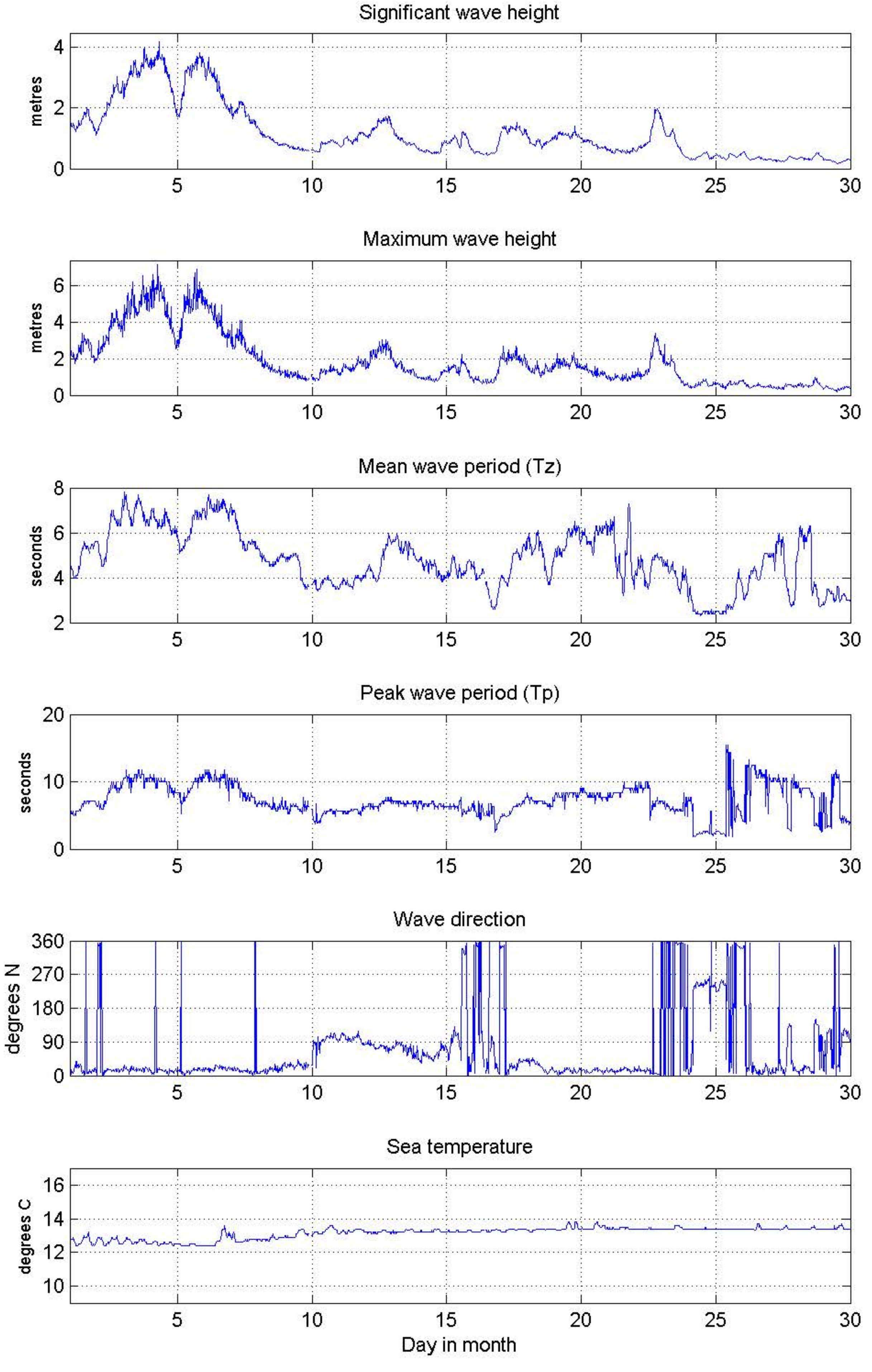
Scarborough - July 2015



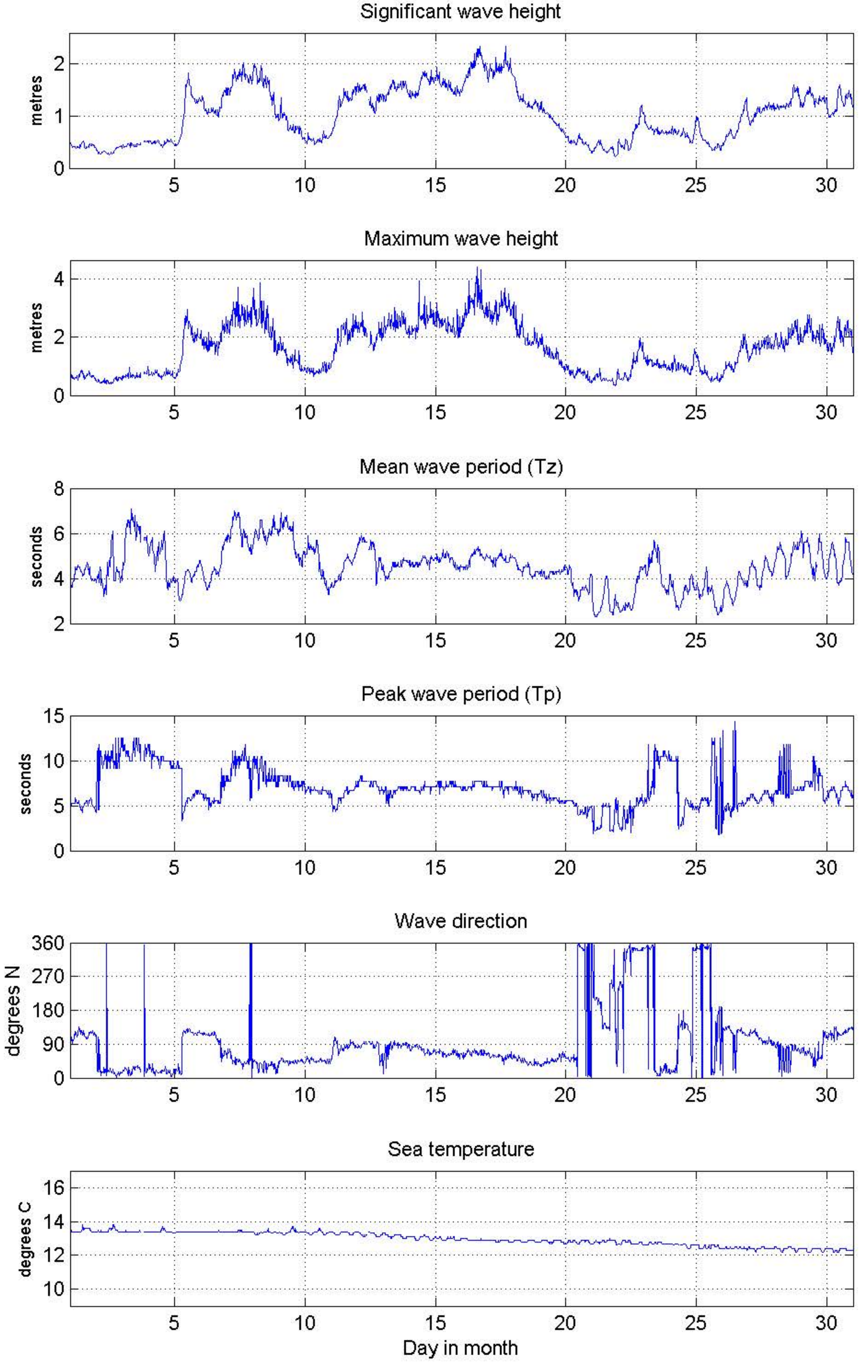
Scarborough - August 2015



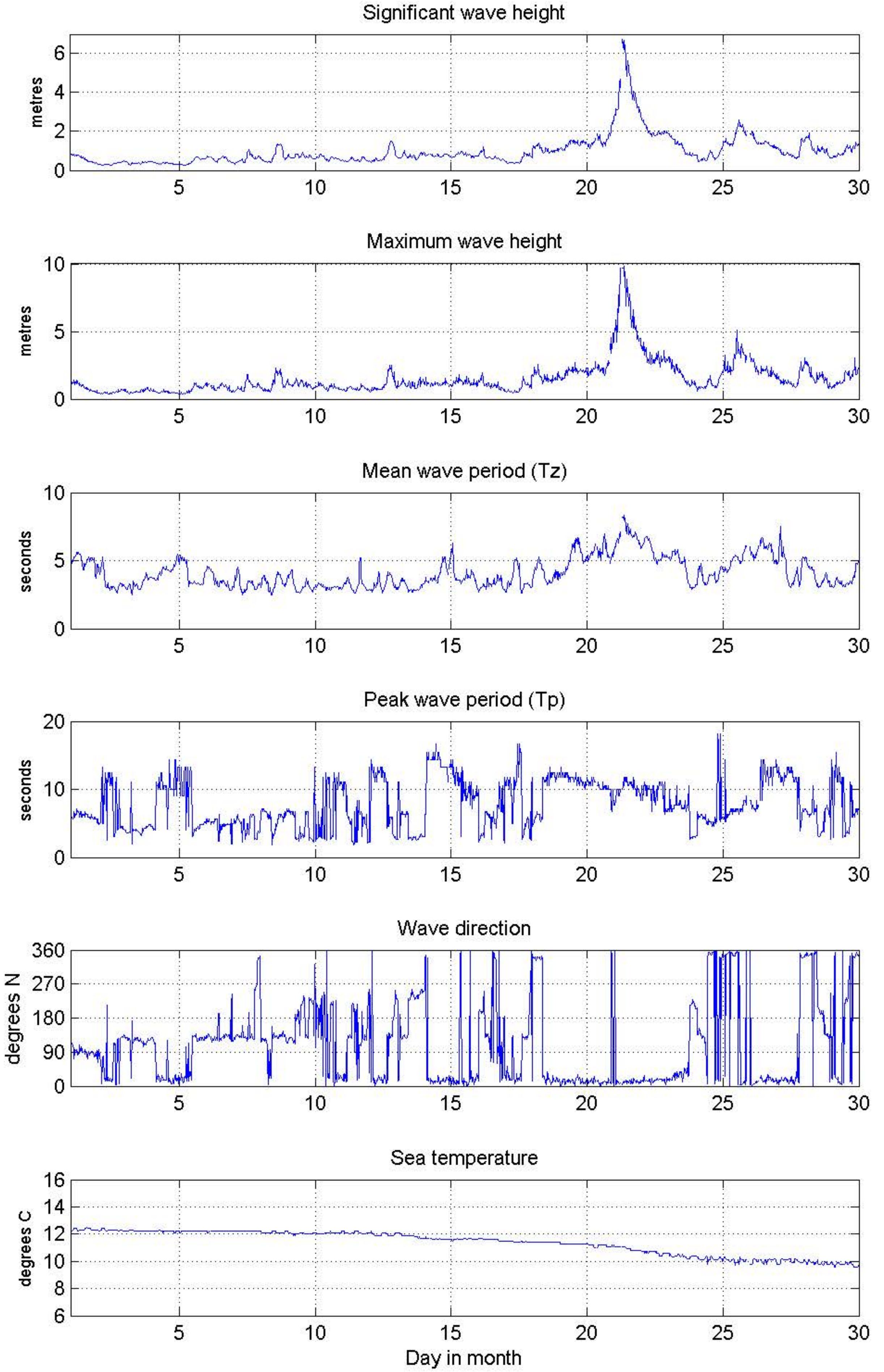
Scarborough - September 2015



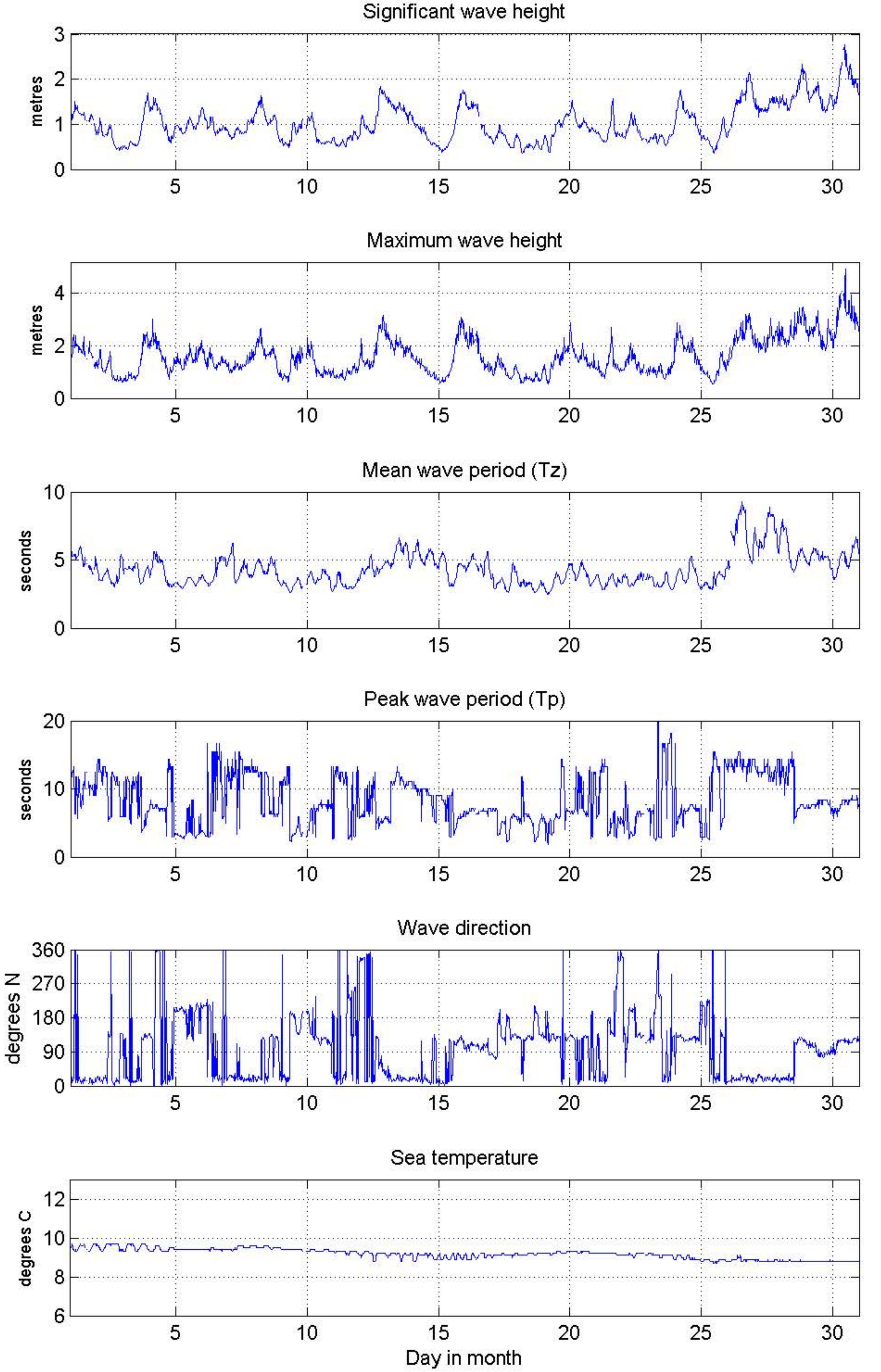
Scarborough - October 2015



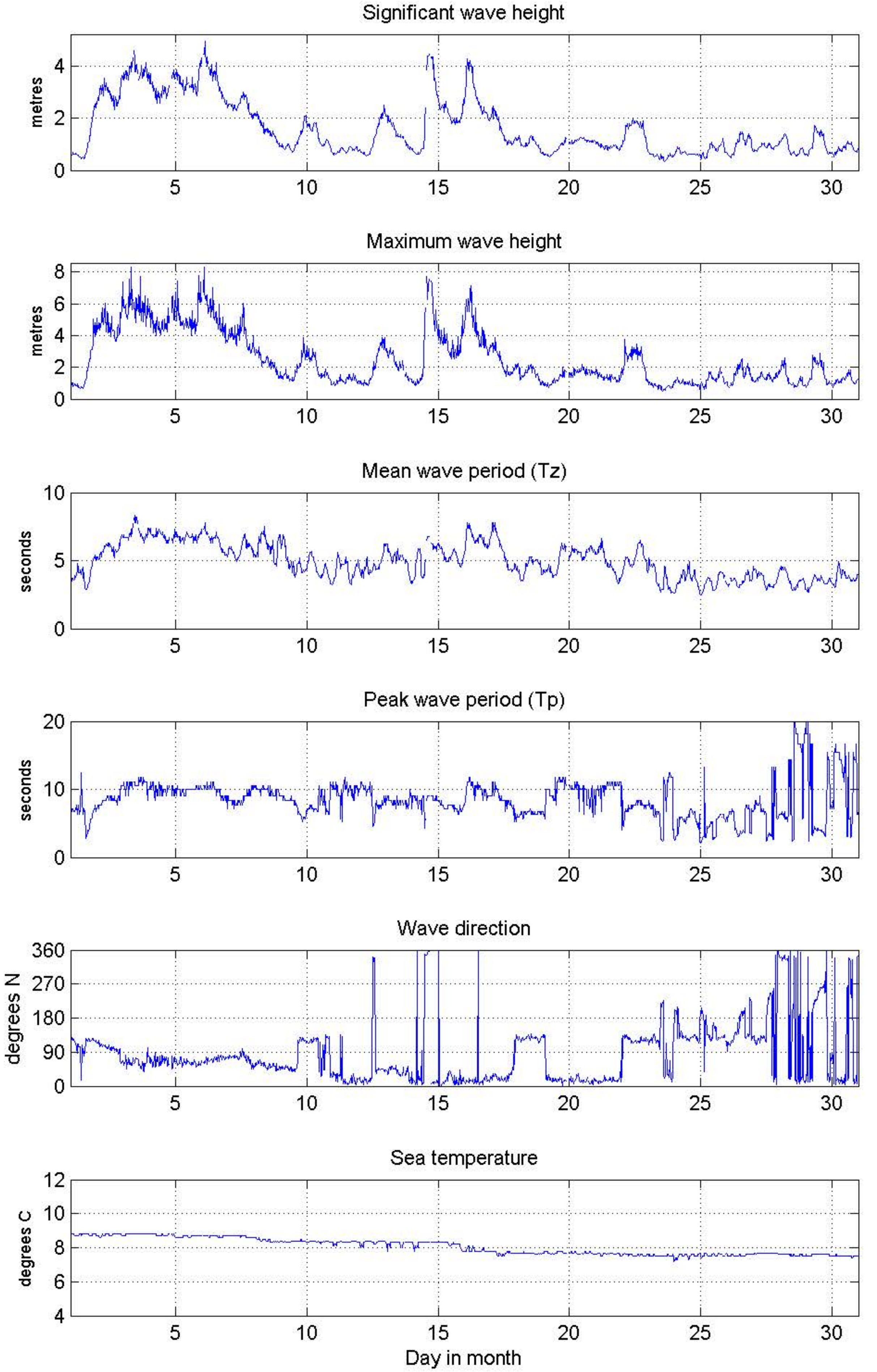
Scarborough - November 2015



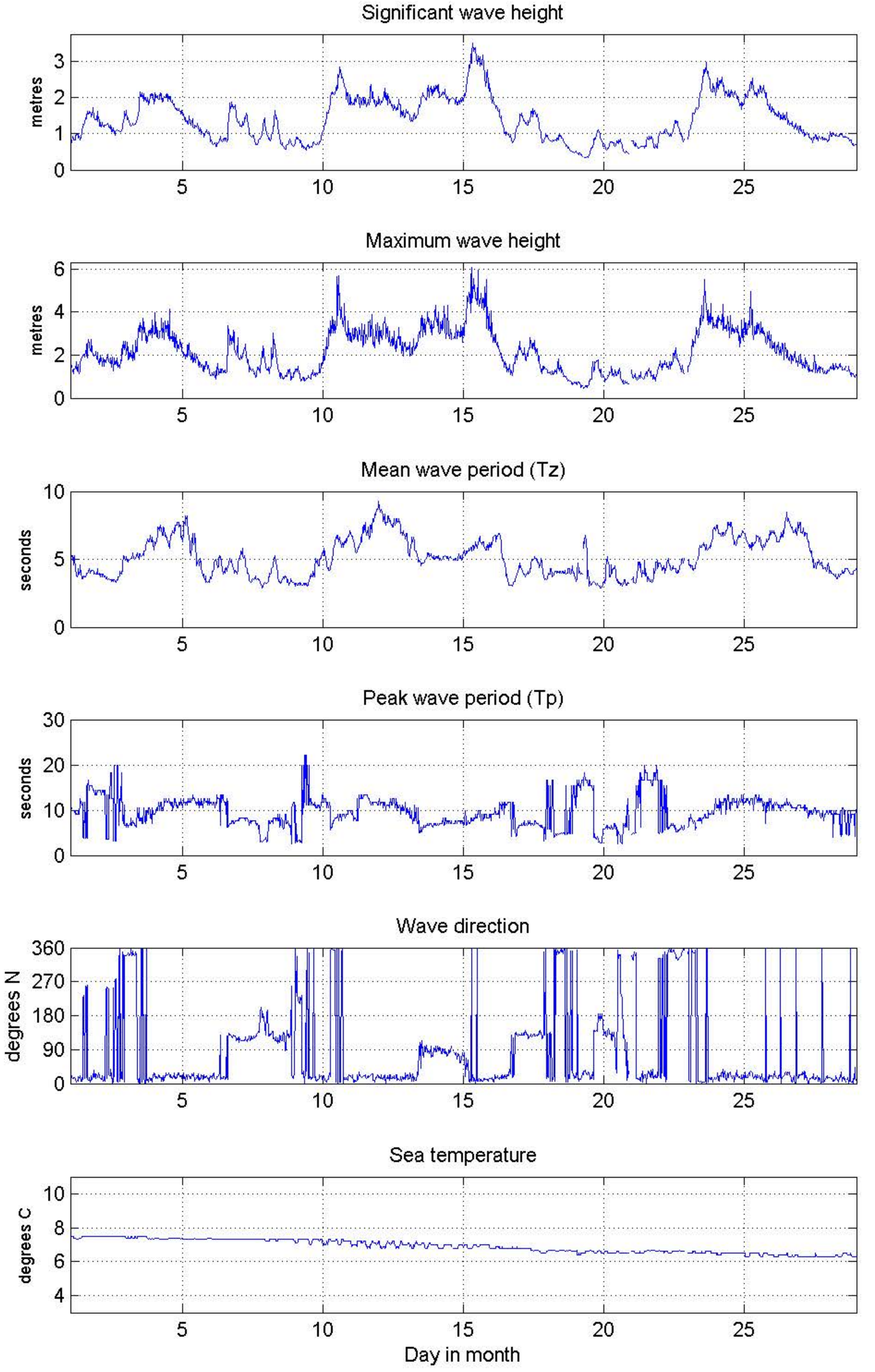
Scarborough - December 2015



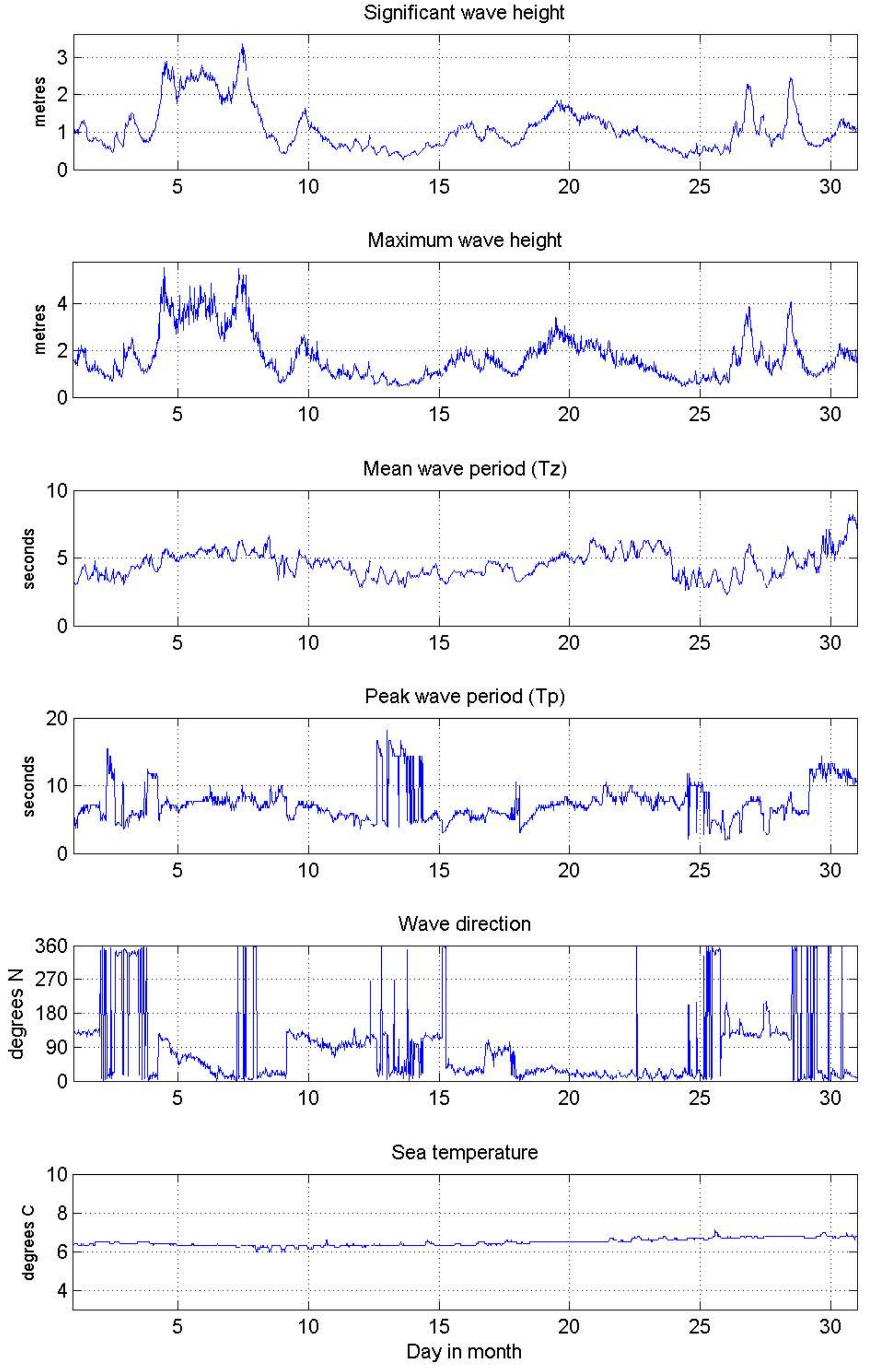
Scarborough - January 2016



Scarborough - February 2016



Scarborough - March 2016



Appendix E

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

Whitby Harbour Tide Gauge

Location

OS: 489842E 511247N
WGS84: *Latitude:* 54° 29' 19.0731"N *Longitude:* 00° 36' 52.6886"W

Instrument Type

Valeport Tidemaster (Drück Pressure Transducer). The tide gauge transducer is fixed to a weighted stainless steel strop located in a stilling well.

Benchmarks

Benchmark	*Description*
TGBM = 4.453m above Ordnance Datum Newlyn	SW Bolt on mooring bollard adjacent to tide gauge, 50 mm above ground on fish quay outside Watch Keeper's Office (54° 29' 19.210"N, 000° 36' 52.620"W)

TGZ = 3.403 m below Ordnance Datum Newlyn

TGZ = 0.403 m below Chart Datum

TGZ = 7.856 m below TGBM

Datum

All data are to Ordnance Datum Newlyn. The height of Chart Datum relative to Ordnance Datum at Whitby is -3.00 m (Admiralty Tide Tables, Supplementary Table III).

Survey information

The site was surveyed on 05 September 2013.

Site characteristics

The tide gauge is located beneath the Fish Quay on the western side of the River Esk, 600 m from the Whitby Harbour entrance.

Data Quality

Recovery rate (%)	Sample interval
98	10 minutes

Service history

The gauge was first deployed on 8 May 2013 and is serviced at 6-monthly intervals.

Measurements

The pressure transducer samples at 8 Hz. Tidal elevations are derived every 1 minute, as the average of the 8 Hz readings over a 30 s burst. The time stamp is the start of the measuring burst. Data readings on the hour and at 10 minute intervals are transmitted.

Residuals and Elevations (OD and CD) for the whole year are shown in Figures 1 to 3 respectively.

Statistics

All times GMT

Month	Extreme maxima		Extreme minima	
	Elevation (OD)	Date/Time	Elevation (OD)	Date/Time
January	3.13	10-Jan-2015 18:40	-2.78	22-Jan-2015 23:40
February	3.18	21-Feb-2015 17:40	-2.64	20-Feb-2015 23:20
March	3.15	23-Mar-2015 18:00	-3.00	21-Mar-2015 23:00
April	2.78	19-Apr-2015 16:30	-2.71	18-Apr-2015 22:00
May	2.81	18-May-2015 16:00	-2.29	17-May-2015 21:40
June	2.59	18-Jun-2015 04:50	-2.16	05-Jun-2015 12:00
July	2.64	05-Jul-2015 06:00	-2.37	04-Jul-2015 11:30
August	3.06	31-Aug-2015 04:40	-2.69	31-Aug-2015 11:00
September	3.15	02-Sep-2015 06:00	-2.89	29-Sep-2015 10:40
October	3.10	28-Oct-2015 03:40	-2.56	29-Oct-2015 11:00
November	3.10	27-Nov-2015 16:50	-2.44	26-Nov-2015 10:10
December	3.04	25-Dec-2015 15:40	-2.36	29-Dec-2015 00:20

Month	Surge maxima		Surge minima	
	Value (m)	Date/Time	Value (m)	Date/Time
January	1.15	10-Jan-2015 17:10	-0.48	15-Jan-2015 06:50
February	0.67	01-Feb-2015 07:50	-0.45	28-Feb-2015 04:20
March	1.12	10-Mar-2015 09:40	-0.66	09-Mar-2015 20:00
April	0.62	01-Apr-2015 00:20	-0.20	04-Apr-2015 11:30
May	0.50	05-May-2015 02:00	-0.18	23-May-2015 15:30
June	0.43	03-Jun-2015 00:40	-0.30	01-Jun-2015 22:20
July	0.51	08-Jul-2015 11:50	-0.15	10-Jul-2015 05:30
August	0.35	05-Aug-2015 05:00	-0.11	03-Aug-2015 14:10
September	0.47	05-Sep-2015 12:10	-0.24	28-Sep-2015 11:40
October	0.99	22-Oct-2015 18:40	-0.27	23-Oct-2015 09:10
November	1.18	13-Nov-2015 12:10	-0.35	08-Nov-2015 20:40
December	0.83	22-Dec-2015 22:10	-0.71	30-Dec-2015 05:50

Month	**Mean Level**	
	No. of days	Elevation (OD)
January	31	0.385
February	28	0.228
March	31	0.209
April	30	0.200
May	31	0.265
June	30	0.226
July	31	0.301
August	31	0.323
September	30	0.336
October	31	0.359
November	30	0.490
December	31	0.418

Highest values in 2015			
Extreme		**Surge**	
Elevation (OD) *(Surge component)*	Date/Time	Value (m)	Date/Time
3.18 *(0.31)*	21-Feb-2015 17:40	1.18	13-Nov-2015 12:10
3.15 *(0.27)*	02-Sep-2015 06:00	1.17	13-Nov-2015 12:40
3.15 *(0.44)*	23-Mar-2015 18:00	1.15	10-Jan-2015 17:10
3.15 *(0.20)*	01-Sep-2015 05:10	1.14	10-Jan-2015 14:10
3.13 *(1.13)*	10-Jan-2015 18:40	1.12	10-Mar-2015 09:40
3.10 *(0.44)*	27-Nov-2015 16:50	1.09	21-Nov-2015 04:10
3.10 *(0.16)*	28-Oct-2015 03:40	1.07	09-Jan-2015 14:20
3.09 *(0.25)*	20-Feb-2015 16:50	0.99	09-Jan-2015 14:00
3.06 *(0.19)*	31-Aug-2015 04:40	0.99	22-Oct-2015 18:40
3.05 *(0.26)*	27-Oct-2015 03:00	0.98	12-Jan-2015 15:50

Year	Annual extreme maxima		Annual surge maxima		Z_0 (OD)	Annual recovery rate
	Elevation (OD) *(Surge)*	Date/Time	Value (m)	Date/Time		
2014	3.15 *(0.31)*	13-Aug-2014 05:20	1.06	21-Oct-2014 20:20	-	95%
2015	3.18 *(0.31)*	21-Feb-2015 17:40	1.18	13-Nov-2015 12:10	-	98%

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

General

The time series of 10 minute tidal elevations for one year is quality-checked in accordance with ESEAS guidelines, flagged and archived. The archived time series is continuous and monotonic, with missing data given as 9999. The missing data shown are days where the entire 24 hours of data are missing.

Monthly extreme maxima/minima are the maximum and minimum water levels from all measured data for that month. Monthly surge maxima/minima (residuals) are calculated in a similar manner from the time series of residuals. Residuals are derived as the measured tidal elevation minus the predicted tidal elevation.

The monthly Mean Level is calculated as the average of all readings for the given month. The annual Z_0 is the value of Mean Sea Level derived by the harmonic analysis of the year's data. These values should not be used for any purpose without consideration of the recovery rate.

Acknowledgement

Tidal predictions were produced by FUGRO EMU Limited.

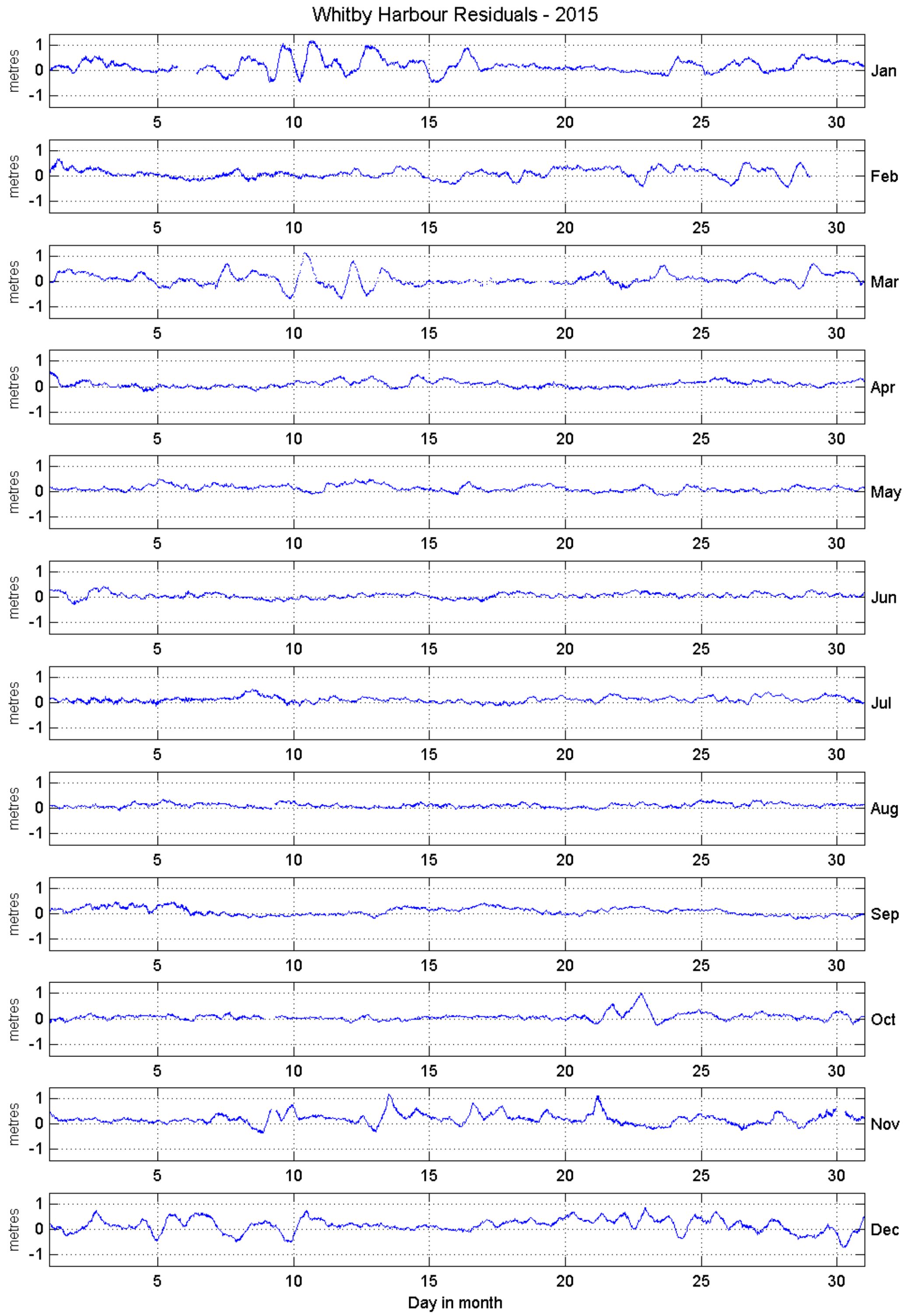


Figure 1: Whitby Harbour residuals for 2015

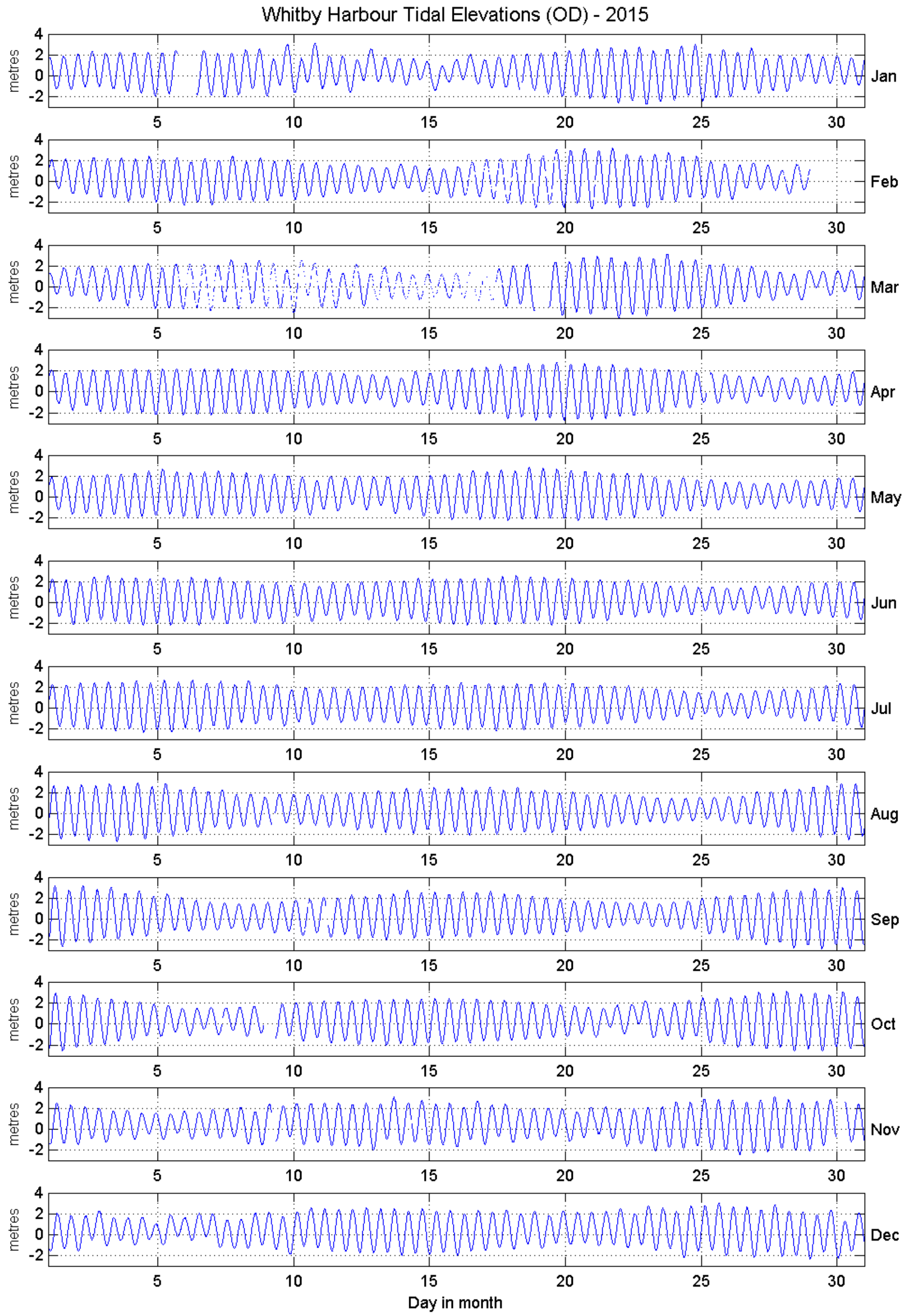


Figure 2: Whitby Harbour tidal elevations for 2015 relative to Ordnance Datum

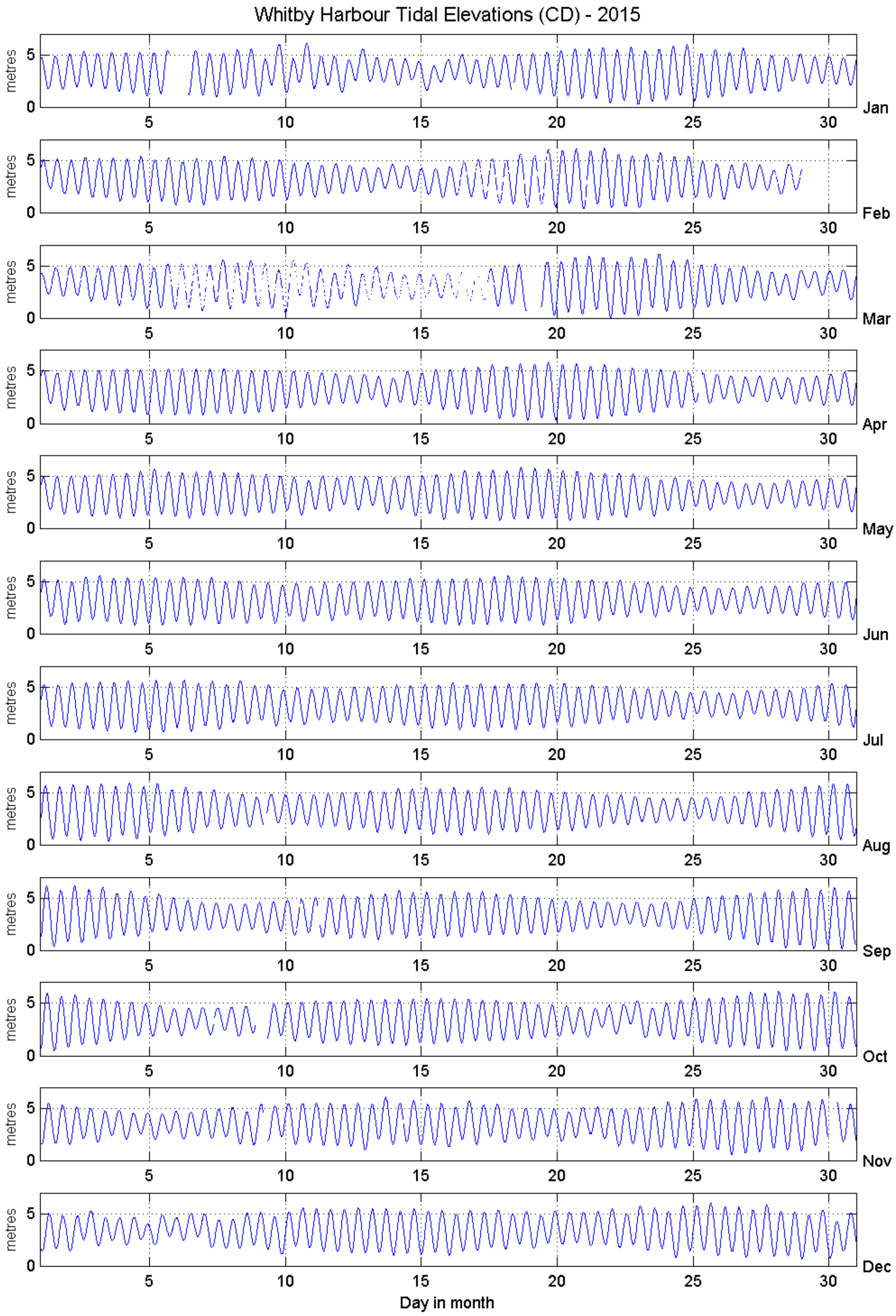


Figure 3: Whitby Harbour tidal elevations for 2015 relative to Chart Datum

Scarborough Tide Gauge

Location

OS: 504898E 488622N
WGS84: *Latitude:* 54° 16' 56.990"N *Longitude:* 00° 23' 25.0279"W

Instrument Type

Valeport 740 (Druck Pressure Transducer)

Benchmarks

Benchmark	*Description*
TGBM = 4.18m above Ordnance Datum Newlyn	Port BM on western slipway of inner harbour 504750.75E 488754.385N

TGZ = -2.52m above Ordnance Datum Newlyn

TGZ = 0.73m above Chart Datum

TGZ = 6.70m below TGBM

Datum

All data are to Ordnance Datum Newlyn. The height of Chart Datum relative to Ordnance Datum at Scarborough is -3.25m (Admiralty Tide Tables, Supplementary Table III).

Survey information

The site was surveyed on 13 June 2013, where the tide gauge offset was found to be 0.195m higher than on the previous survey in 2003. The datum appeared to have changed during the period 2006-2011.

Site characteristics

The pressure transducer is mounted in a stilling well in Scarborough harbour.

Data Quality

Recovery rate (%)	Sample interval
98	10 minutes

Service history

The gauge was first deployed on 28 April 2003 and maintained until December 2005. Measurements continued, and full maintenance was resumed in 2011.

Measurements

The pressure transducer samples at 4Hz. Tidal elevations are derived, every 10 minutes, as the 40 second average of the 4Hz readings. The time stamp is the start of the measuring burst. Although the time stamp is accurate, the instrument has to be started manually after servicing and it is not always possible to start exactly on a 10 minute integer. Measurements are interpolated to the hour and 10 minute intervals, if the original time series is not on the hour. Missing data exceeding 2 hours are not interpolated. All data measured prior to the gauge being fully surveyed were adjusted to the correct elevations, but it has proven difficult to establish where the datum changed occurred between 2006 and 2011. The highest values during these years are included in the Amax tables, since the date/times are valid, but the elevations should be used with caution.

Residuals and Elevations (OD and CD) for the whole year are shown in Figures 1 to 3 respectively.

Statistics

All times GMT

Month	Extreme maxima		Extreme minima	
	Elevation (OD)	Date/Time	Elevation (OD)	Date/Time
January	3.17	10-Jan-2015 18:50	-2.50	23-Jan-2015 00:30
February	3.29	21-Feb-2015 17:40	-2.46	20-Feb-2015 23:50
March	3.26	23-Mar-2015 18:10	-2.58	22-Mar-2015 00:00
April	2.93	19-Apr-2015 16:30	-2.53	18-Apr-2015 22:30
May	2.92	18-May-2015 16:10	-2.27	17-May-2015 22:10
June	2.70	18-Jun-2015 05:00	-2.17	05-Jun-2015 11:50
July	2.77	05-Jul-2015 06:10	-2.30	04-Jul-2015 12:00
August	3.20	31-Aug-2015 04:40	-2.46	31-Aug-2015 11:30
September	3.26	02-Sep-2015 06:10	-2.49	28-Sep-2015 10:30
October	3.20	28-Oct-2015 04:00	-2.41	01-Oct-2015 12:30
November	3.20	27-Nov-2015 17:10	-2.42	26-Nov-2015 10:20
December	3.15	25-Dec-2015 15:50	-2.39	29-Dec-2015 00:30

Month	Surge maxima		Surge minima	
	Value (m)	Date/Time	Value (m)	Date/Time
January	1.23	10-Jan-2015 17:30	-0.63	15-Jan-2015 07:10
February	0.57	26-Feb-2015 16:10	-0.45	28-Feb-2015 04:20
March	1.10	10-Mar-2015 10:50	-0.71	11-Mar-2015 18:10
April	0.76	01-Apr-2015 00:40	-0.21	08-Apr-2015 14:20
May	0.49	12-May-2015 19:10	-0.16	23-May-2015 18:10
June	0.39	03-Jun-2015 00:20	-0.35	01-Jun-2015 22:10
July	0.53	08-Jul-2015 13:30	-0.16	10-Jul-2015 05:40
August	0.29	09-Aug-2015 19:40	-0.21	19-Aug-2015 20:00
September	0.36	03-Sep-2015 11:50	-0.35	28-Sep-2015 11:30
October	0.80	22-Oct-2015 19:10	-0.42	23-Oct-2015 09:20
November	1.06	13-Nov-2015 13:00	-0.48	08-Nov-2015 18:30
December	0.78	22-Dec-2015 23:00	-0.73	30-Dec-2015 06:20

Month	Mean Level	
	No. of days	Elevation (OD)
January	31	0.401
February	28	0.251
March	31	0.235
April	30	0.238
May	31	0.300
June	29	0.254
July	29	0.331
August	31	0.354
September	30	0.393
October	31	0.397
November	30	0.522
December	31	0.444

Highest values in 2015			
Extreme		**Surge**	
Elevation (OD) *(Surge component)*	Date/Time	Value (m)	Date/Time
3.29 *(0.29)*	21-Feb-2015 17:40	1.23	10-Jan-2015 17:30
3.26 *(0.08)*	02-Sep-2015 06:10	1.11	09-Jan-2015 14:40
3.26 *(0.41)*	23-Mar-2015 18:10	1.10	10-Mar-2015 10:50
3.25 *(0.00)*	01-Sep-2015 05:30	1.06	12-Jan-2015 17:30
3.21 *(0.21)*	20-Feb-2015 17:00	1.06	13-Nov-2015 13:00
3.20 *(0.00)*	28-Oct-2015 04:00	1.01	13-Nov-2015 12:30
3.20 *(0.02)*	31-Aug-2015 04:40	0.98	09-Jan-2015 14:10
3.20 *(0.38)*	27-Nov-2015 17:10	0.92	21-Nov-2015 04:00
3.17 *(1.14)*	10-Jan-2015 18:50	0.91	12-Jan-2015 15:50
3.16 *(0.11)*	27-Oct-2015 03:10	0.88	10-Mar-2015 15:10

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

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

General

The time series of 10 minute tidal elevations for one year is quality-checked in accordance with ESEAS guidelines, flagged and archived. The archived time series is continuous and monotonic, with missing data given as 9999. The missing data shown are days where the entire 24 hours of data are missing.

Monthly extreme maxima/minima are the maximum and minimum water levels from all measured data for that month. Monthly surge maxima/minima (residuals) are calculated in a similar manner from the time series of residuals. Residuals are derived as the measured tidal elevation minus the predicted tidal elevation.

The monthly Mean Level is calculated as the average of all readings for the given month. The annual Z_0 is the value of Mean Sea Level derived by the harmonic analysis of the year's data. These values should not be used for any purpose without consideration of the recovery rate.

Acknowledgement

Tidal predictions were produced using the TASK windows edition software, kindly provided by the Marine Data Products team at the UK National Oceanography Centre (Liverpool).

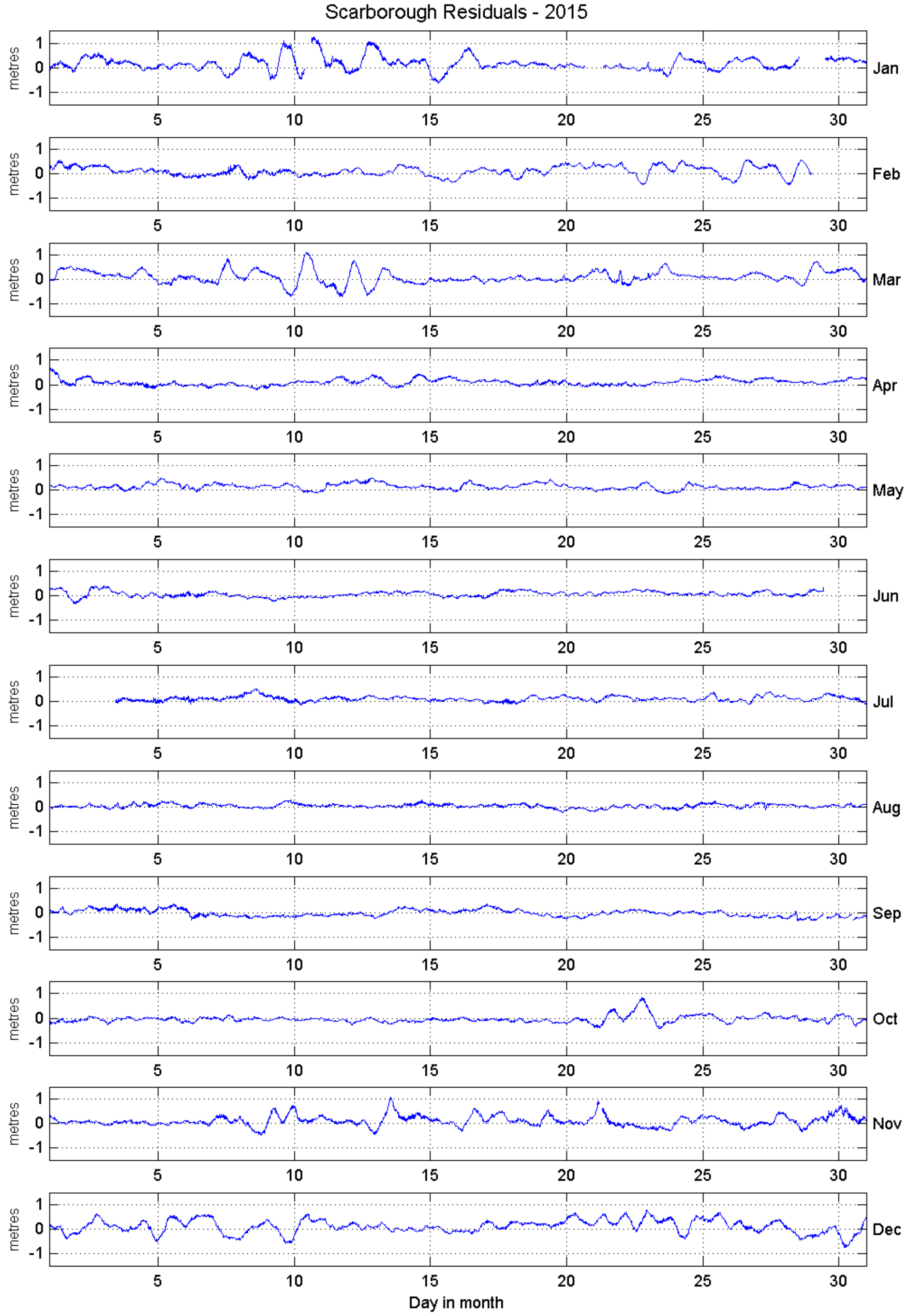


Figure 1: Scarborough residuals for 2015

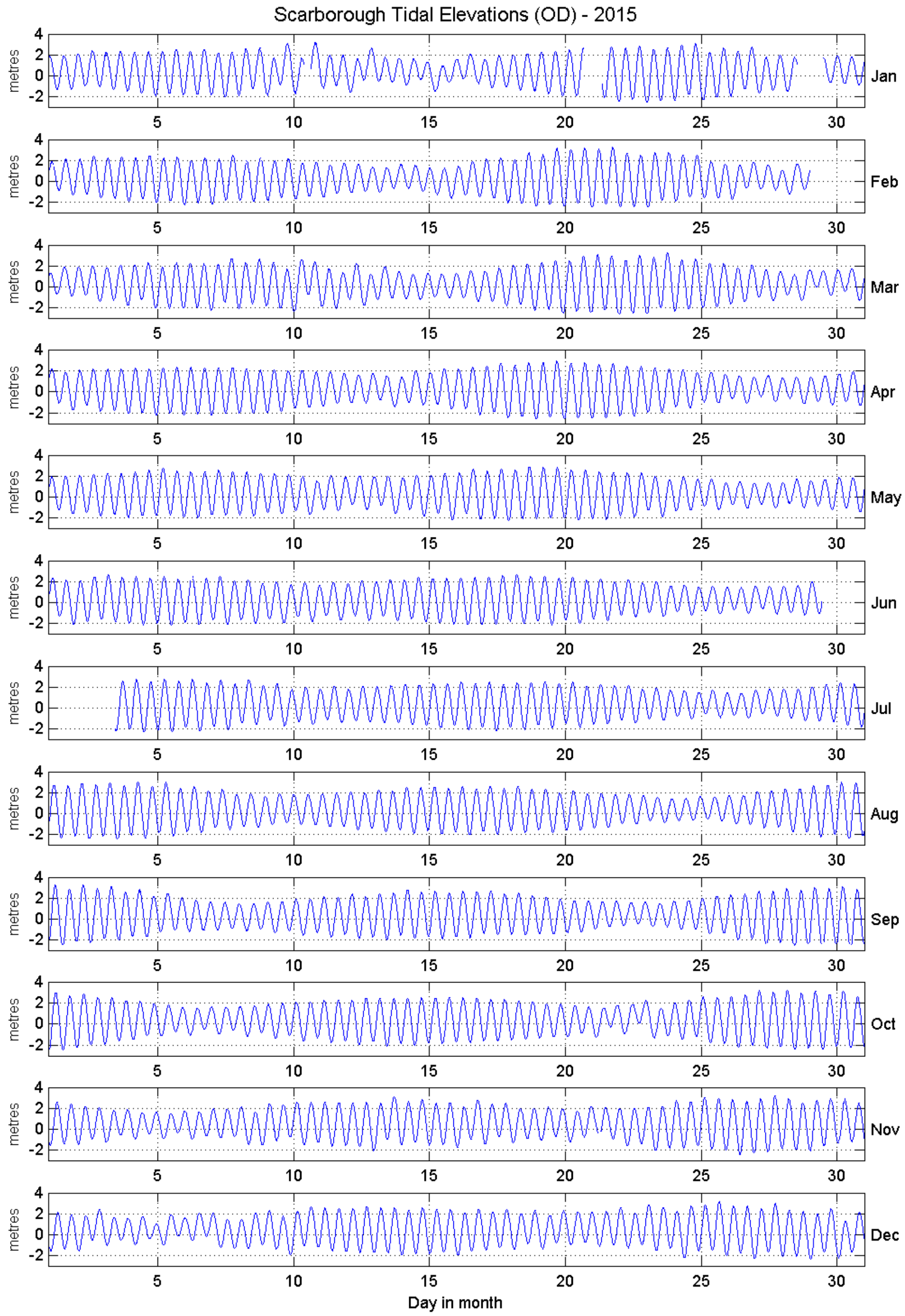


Figure 2: Scarborough tidal elevations for 2015 relative to Ordnance Datum

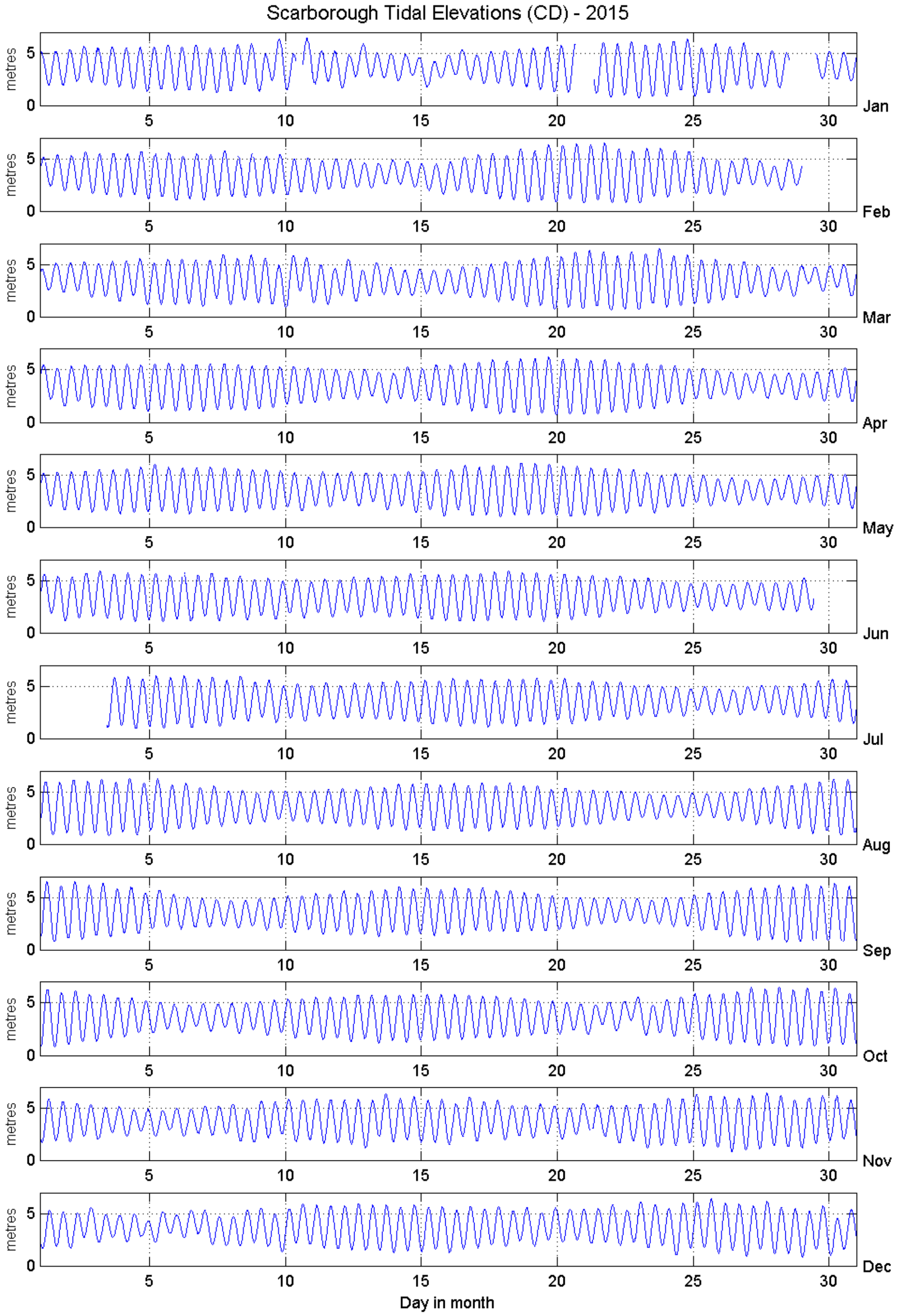


Figure 3: Scarborough tidal elevations for 2015 relative to Chart Datum

Newbiggin Directional Waverider Buoy

<table>
<tr><th colspan="2">Location</th><td rowspan="5"></td><td rowspan="5">
</td></tr>
<tr><td>OS</td><td>433318 E 588000 N</td></tr>
<tr><td>WGS84</td><td>Latitude: 55° 11.11' N
Longitude: 01° 28.70' W</td></tr>
<tr><th colspan="2">Instrument type</th></tr>
<tr><td colspan="2">Datawell
Directional Waverider Mk III</td></tr>
<tr><th>Water depth</th><td>~18m CD</td><td>Buoy in situ off Newbiggin-by-the-Sea. Photo courtesy of Fugro EMU Limited</td><td>Location of buoy (Google mapping)</td></tr>
</table>

Data Quality

Recovery rate (%)	Sample interval
99	30 minutes

Monthly Averages - 2015

All times are GMT

Month	H_s (m)	T_p (s)	T_z (s)	Dir. (°)	SST (°C)	No. of days
January	0.88	10.3	4.4	87	7.3	31
February	1.05	9.8	4.9	74	6.1	28
March	0.87	7.8	4.4	91	6.2	31
April	0.65	8.6	4.5	63	7.4	30
May	0.72	7.4	4.2	73	8.7	31
June	0.62	6.7	4.3	75	10.5	30
July	0.86	6.9	4.5	72	11.9	31
August	0.71	5.8	4.1	98	12.7	31
September	0.95	6.8	4.6	67	12.8	30
October	1.01	6.9	4.6	91	12.1	30
November	0.76	7.8	4.3	93	10.8	30
December	1.14	7.3	4.6	109	9.2	30

Storm Analysis

Date/Time	H_s (m)	T_p (s)	T_z (s)	Dir. (°)	Water level elevation* (OD)	Tidal stage (hours re. HW)	Tidal range (m)	Tidal surge* (m)	Max. surge* (m)
21-Nov-2015 04:30	4.74	10.0	7.3	38	-0.64	HW +6	2.8	0.50	0.72
01-Feb-2015 02:00	3.50	10.0	6.6	38	1.77	HW	2.8	-0.05	0.19
03-May-2015 12:30	3.36	8.3	6.1	107	0.83	HW -3	3.6	0.06	0.12
21-Mar-2015 14:30	3.25	10.0	6.8	44	2.14	HW -1	4.8	-0.18	-0.11
30-Dec-2015 11:30	3.07	9.1	5.8	114	-1.17	HW +5	2.7	-0.26	-0.11

Annual Statistics

Year	Annual H_s exceedance* (m)						Annual Maximum H_s	
	0.05%	0.5%	1%	2%	5%	10%	Date	A_{max} (m)
2013	-	3.26	3.04	2.71	2.27	1.88	10-Oct-2013 18:30	4.15
2014	3.76	3.27	3.01	2.73	2.24	1.86	19-Jan-2014 20:00	4.22
2015	3.90	2.90	2.66	2.37	1.97	1.61	21-Nov-2015 04:30	4.74

** i.e. 5 % of the H_s values measured in 2013 exceeded 2.27 m*

Distribution plots

The distribution of wave parameters are shown in the accompanying graphs/tables of:

- Annual time series of H_s (red line is 3.0 m storm threshold)
- Wave rose (percentage of occurrence of Direction vs. H_s) for all measured data
- Percentage of occurrence of H_s, T_p, T_z and Direction for 2015
- Incidence of storm waves for 2015. Storm events are defined using the Peaks-over-Threshold method. The highest H_s of each storm event is shown
- Joint distribution of all parameters for all measured data, given as percentage of occurrence

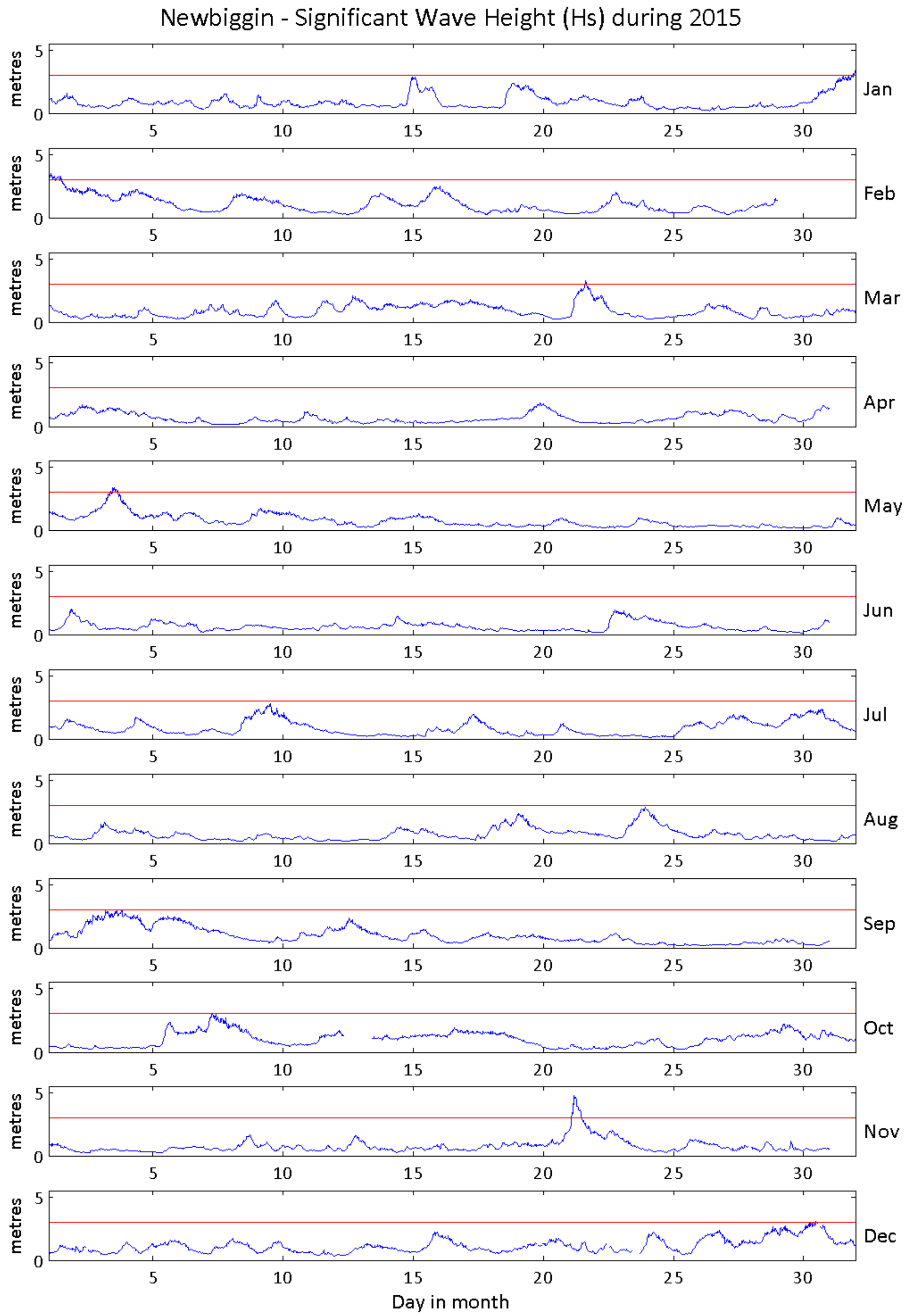
General

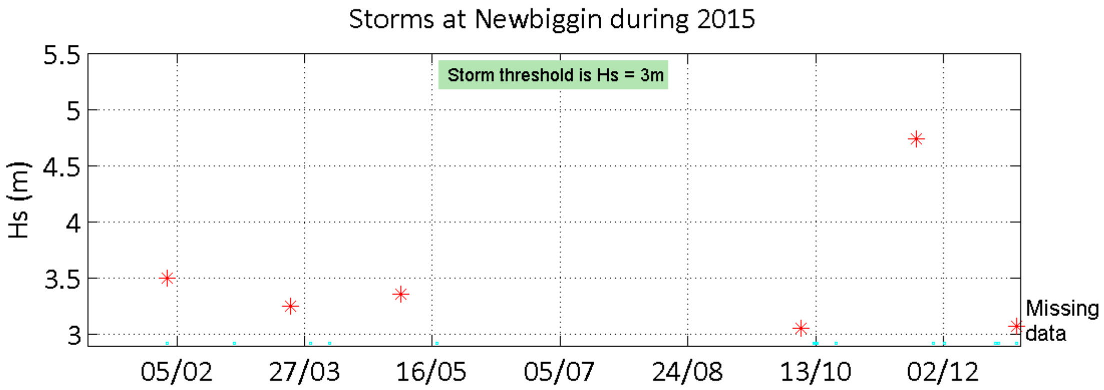
The buoy, owned by Scarborough Borough Council, was deployed on 21 June 2013, at which time the magnetic declination at the site was 2.2° west, changing by 0.18° east per year. A DWR had previously been deployed at this location from 20 May 2010 to 04 February 2011.

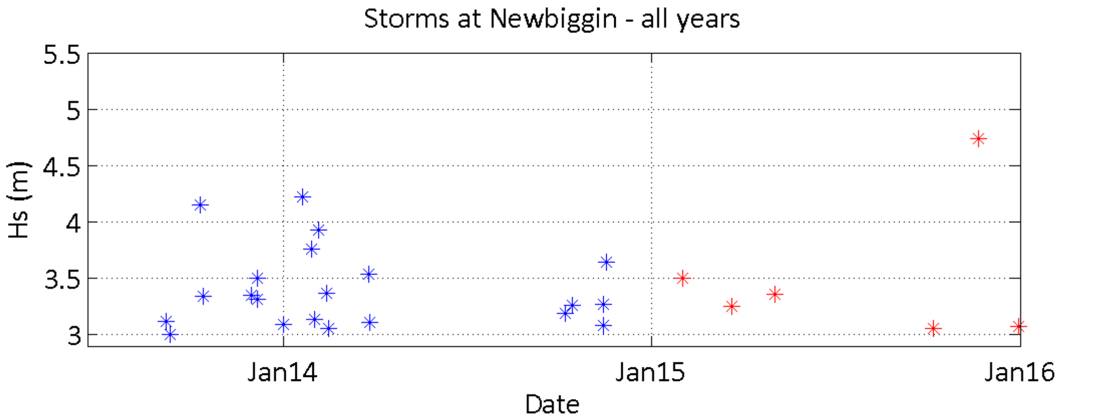
** Tidal information is obtained from the nearest recording tide gauge (the National Network gauge at North Shields). The surge shown is the residual at the time of the highest Hs. The maximum tidal surge is the largest positive surge during the storm event.*

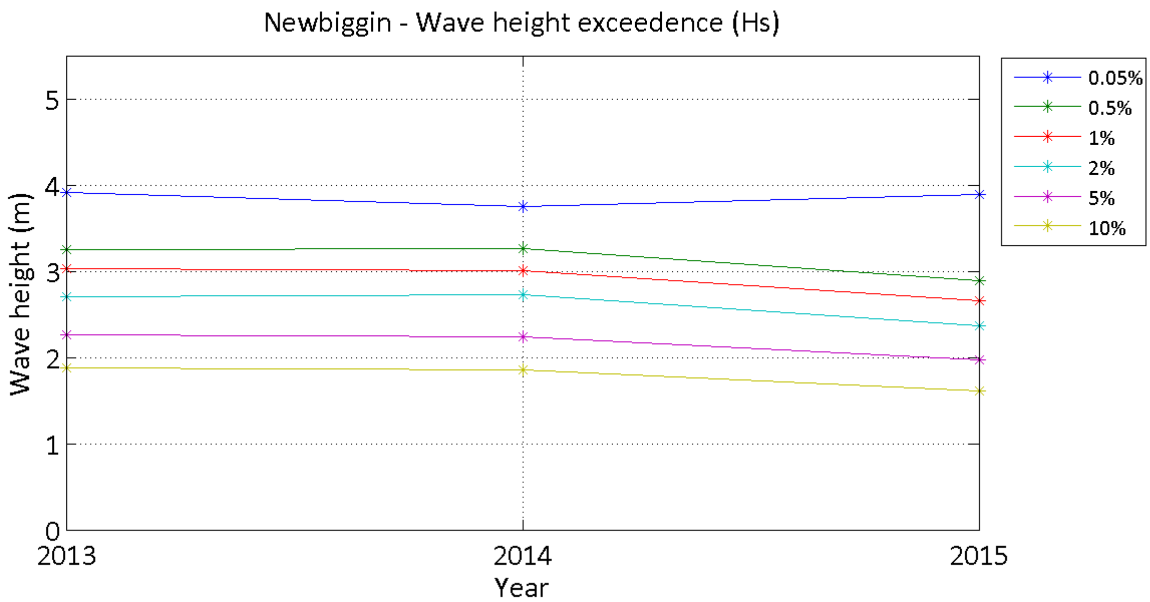
Acknowledgements

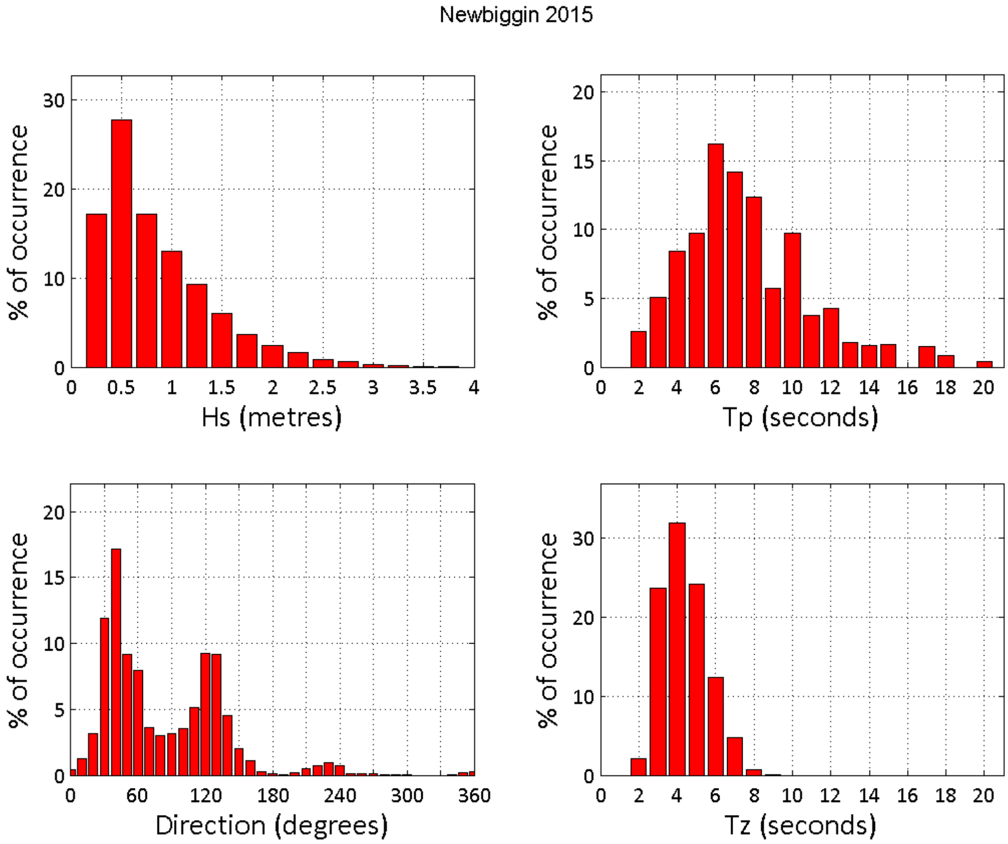
Tidal data were supplied by the British Oceanographic Data Centre as part of the function of the National Tidal and Sea Level Facility, hosted by the Proudman Oceanographic Laboratory and funded by DEFRA and the Natural Environment Research Council.

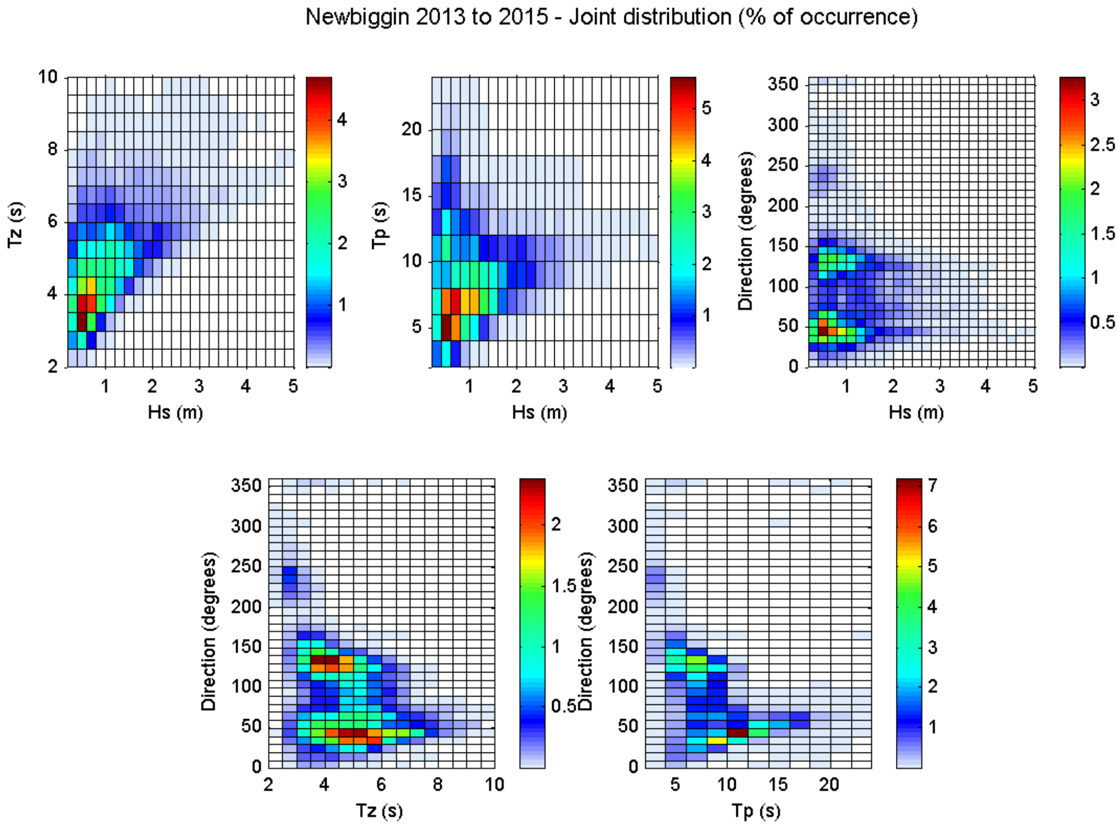

Newbiggin - Significant Wave Height (Hs) during 2015
metres
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0
5
10
15
20
25
30
Day in month

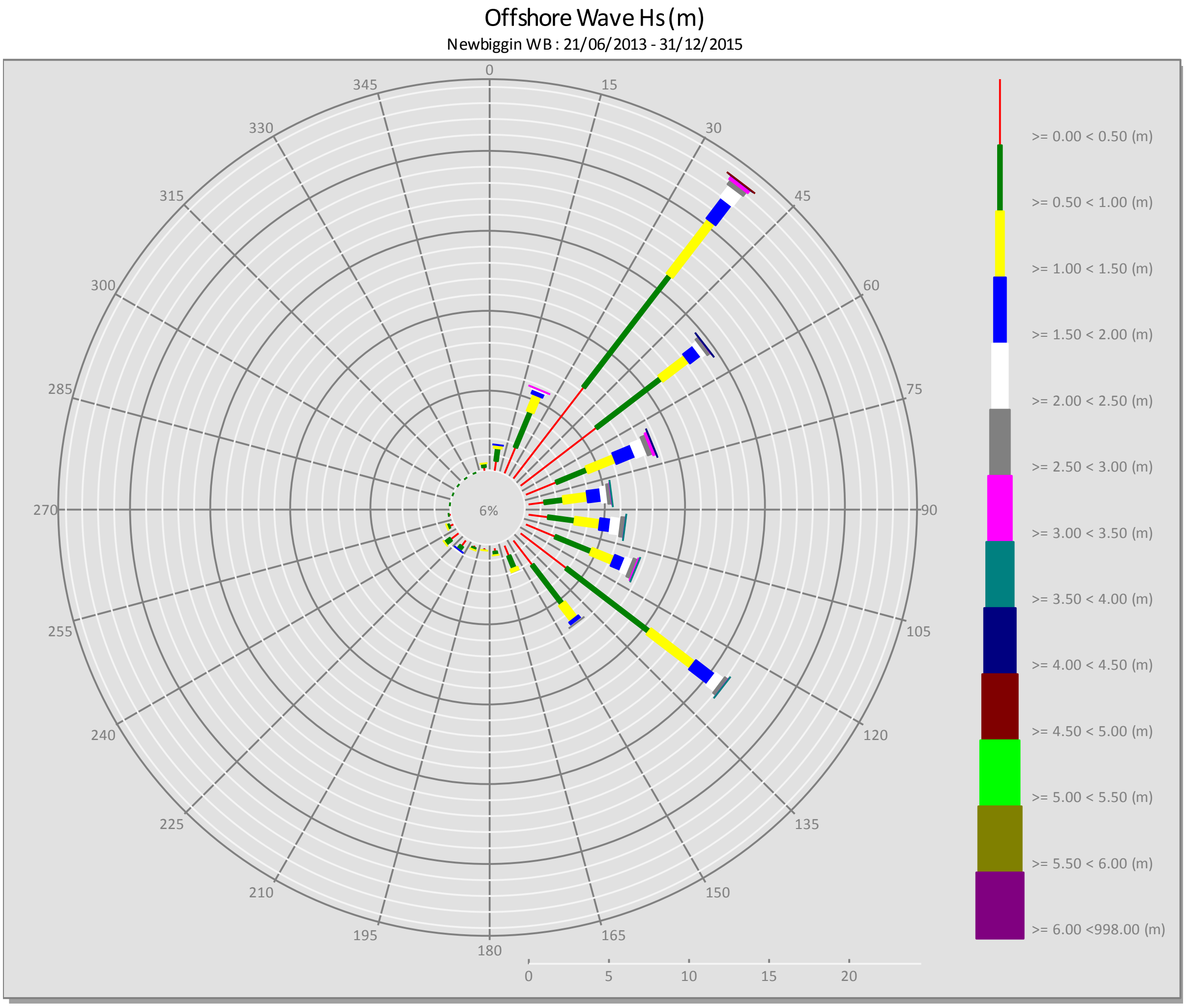

Storms at Newbiggin during 2015
Storm threshold is Hs = 3m
Hs (m)
Missing data
05/02
27/03
16/05
05/07
24/08
13/10
02/12


Storms at Newbiggin - all years
Hs (m)
Jan14
Jan15
Jan16
Date


Newbiggin - Wave height exceedence (Hs)
Wave height (m)
Year
0.05%
0.5%
1%
2%
5%
10%


Newbiggin 2015
% of occurrence
Hs (metres)
Tp (seconds)
Direction (degrees)
Tz (seconds)


Newbiggin 2013 to 2015 - Joint distribution (% of occurrence)
Tz (s)
Tp (s)
Direction (degrees)
Hs (m)



Offshore Wave Hs (m)
Newbiggin WB : 21/06/2013 - 31/12/2015
0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
240
255
270
285
300
315
330
345
6%
0
5
10
15
20
>= 0.00 < 0.50 (m)
>= 0.50 < 1.00 (m)
>= 1.00 < 1.50 (m)
>= 1.50 < 2.00 (m)
>= 2.00 < 2.50 (m)
>= 2.50 < 3.00 (m)
>= 3.00 < 3.50 (m)
>= 3.50 < 4.00 (m)
>= 4.00 < 4.50 (m)
>= 4.50 < 5.00 (m)
>= 5.00 < 5.50 (m)
>= 5.50 < 6.00 (m)
>= 6.00 <998.00 (m)

Whitby Directional Waverider Buoy

Location	
OS	490239 E 513067 N
WGS84	*Latitude:* 54° 30.29' N *Longitude:* 00° 36.48' W
Instrument type	
Datawell Directional Waverider Mk III	
Water depth	~17m CD

Buoy in situ off Whitby beach. Photo courtesy of Fugro EMU Limited

Location of buoy (Google mapping)

Data Quality

Recovery rate (%)	Sample interval
76	30 minutes

Monthly Averages - 2015

All times are GMT

Month	H_s (m)	T_p (s)	T_z (s)	Dir. (°)	SST (°C)	No. of days
January	1.08	10.5	4.9	107	6.8	31
February	1.22	10.9	5.3	60	5.9	28
March	0.95	8.9	4.5	103	6.1	31
April	0.79	9.6	5.0	54	7.4	30
May	1.08	8.1	5.0	65	8.6	11
June	-	-	-	-	-	0
July	1.33	7.5	5.1	35	13.0	8
August	0.61	6.4	4.2	81	13.4	31
September	1.11	7.2	4.8	74	13.5	30
October	0.73	7.5	4.7	107	12.6	18
November	0.85	8.9	4.4	106	10.9	30
December	0.83	10.0	4.7	79	9.0	31

Storm Analysis

Date/Time	H_s (m)	T_p (s)	T_z (s)	Dir. (°)	Water level elevation* (OD)	Tidal stage (hours re. HW)	Tidal range (m)	Tidal surge* (m)	Max. surge* (m)
21-Nov-2015 07:30	6.68⁺	12.5	8.3	14	-	HW -4	~3.1	-	-
01-Feb-2015 02:30	5.69	11.8	7.8	11	2.16	HW	2.7	0.31	0.63
04-Sep-2015 07:00	3.98	9.1	6.3	24	2.78	HW -1	4.2	0.29	0.46
03-Sep-2015 18:30	3.92	10.5	6.5	27	2.52	HW -1	4.4	0.25	0.46
05-Sep-2015 20:30	3.85	10.0	6.9	27	2.11	HW -1	3.0	0.29	0.51

Annual Statistics

Year	Annual H_s exceedance* (m)						Annual Maximum H_s	
	0.05%	0.5%	1%	2%	5%	10%	Date	A_{max} (m)
2013	-	4.76	4.43	3.93	2.98	2.19	10-Oct-2013 20:00	6.26
2014	3.74	3.16	2.81	2.53	2.12	1.75	14-Oct-2014 05:30	4.10
2015	5.60	4.06	3.45	2.97	2.21	1.75	21-Nov-2015 07:30	6.68⁺

** i.e. 5 % of the H_s values measured in 2013 exceeded 2.98 m*

⁺ Note that waves were breaking at the buoy for several hours during this storm; where breaking waves were clearly present in the measured time series, the parameters have been omitted. Accordingly, there may have been short periods where measured significant wave heights exceeded this value.

Distribution plots

The distribution of wave parameters are shown in the accompanying graphs/tables of:

- Annual time series of H_s (red line is 3.25m storm threshold)
- Incidence of storm waves for 2015. Storm events are defined using the Peaks-over-Threshold method. The highest H_s of each storm event is shown
- Wave height exceedance each year since deployment
- Percentage of occurrence of H_s, T_p, T_z and Direction for 2015
- Joint distribution of all parameters for all measured data, given as percentage of occurrence
- Wave rose (percentage of occurrence of direction vs. H_s) for all measured data

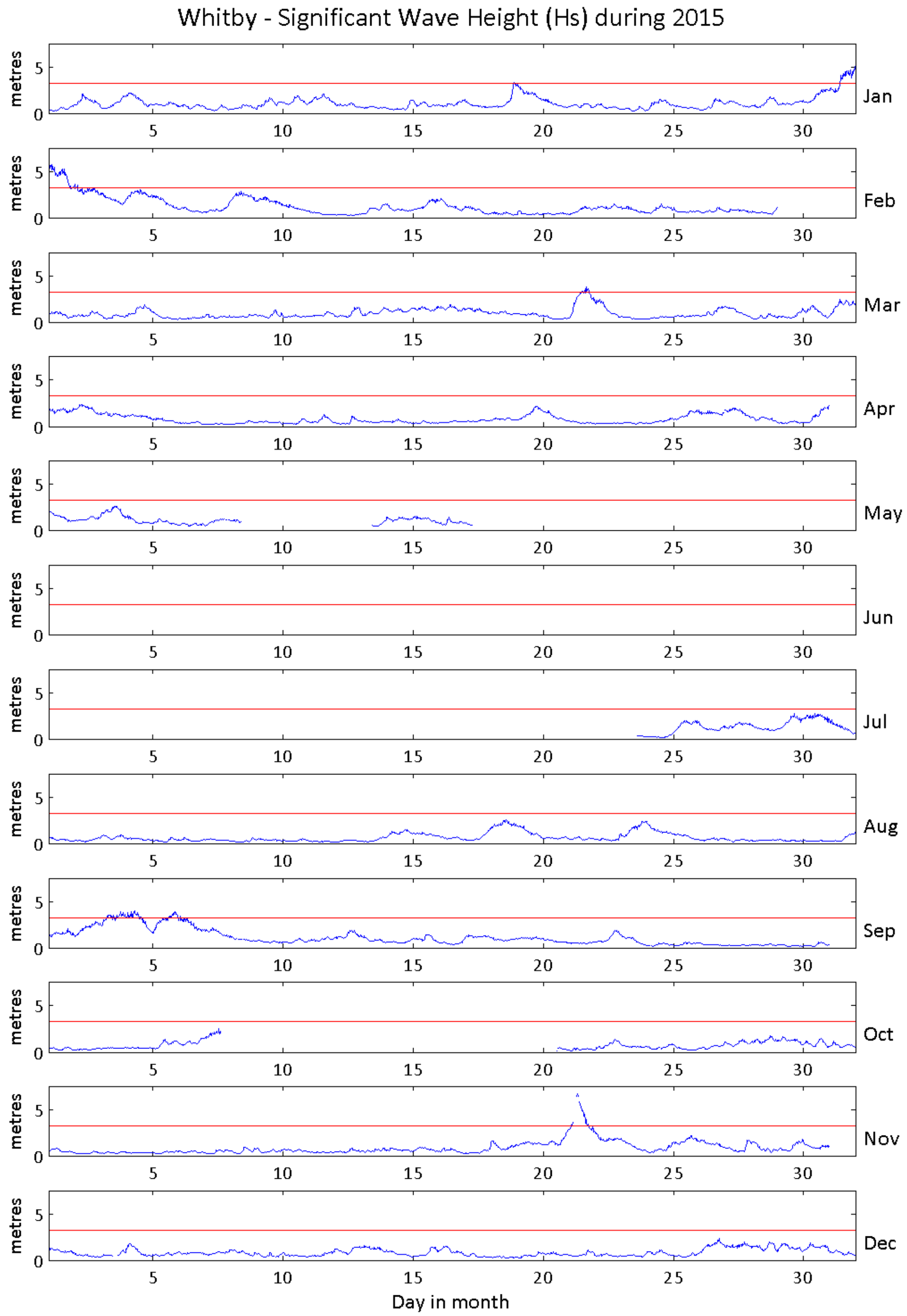
** Tidal information is obtained from the nearest recording tide gauge (the National Network gauge at Whitby). The surge shown is the residual at the time of the highest Hs. The maximum tidal surge is the largest positive surge during the storm event.*

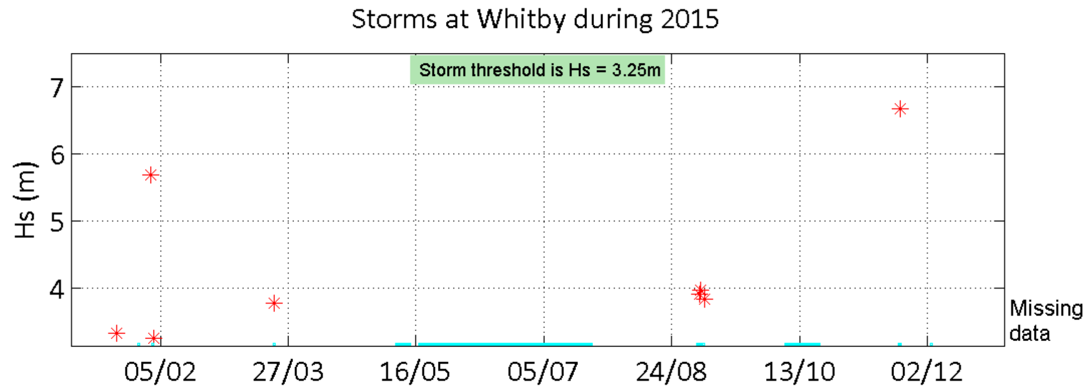
General

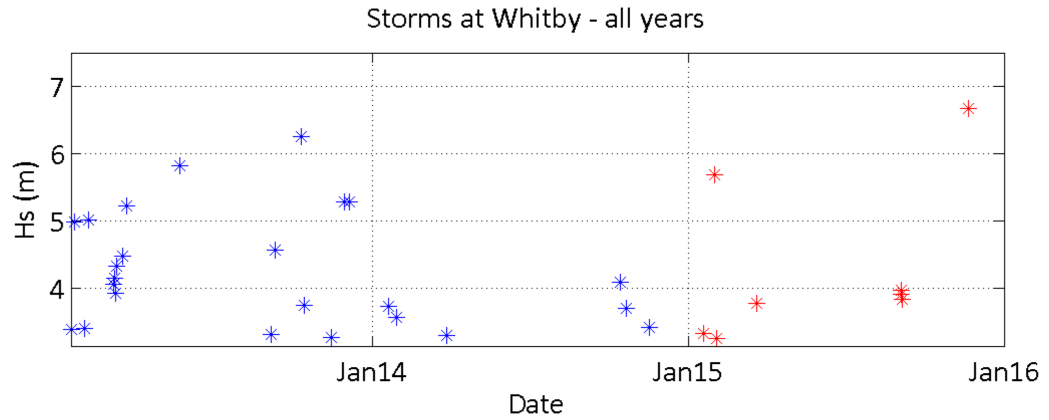
The buoy was deployed on 18 January 2013, at which time the magnetic declination at the site was 1.8° west, changing by 0.18° east per year. A DWR had previously been deployed at this location from 20 May 2010 to 04 February 2011.

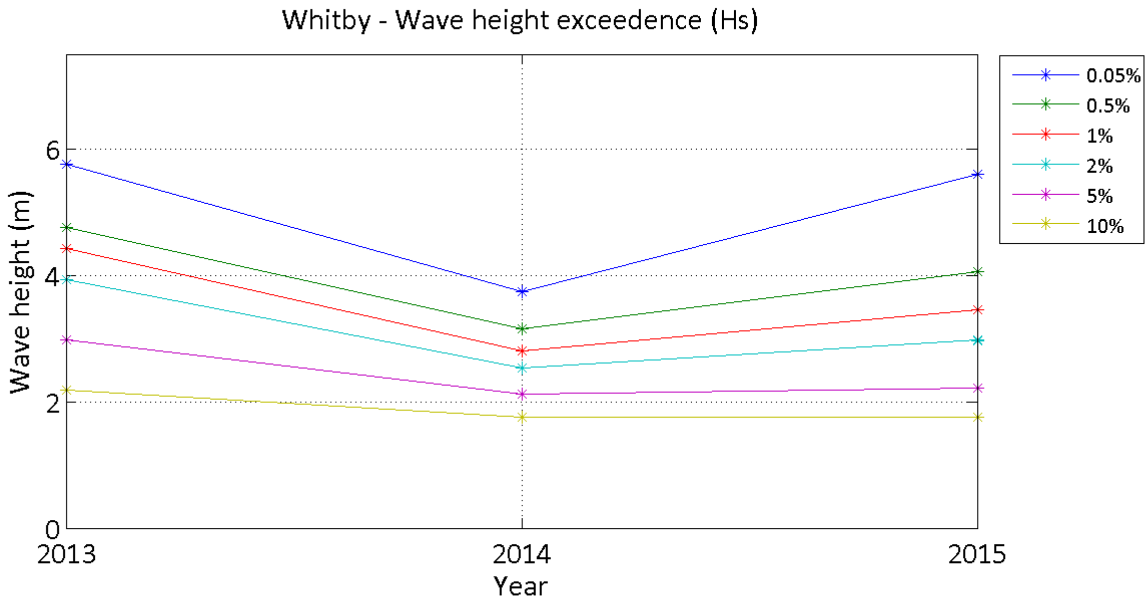
Acknowledgements

Tidal data were supplied by the British Oceanographic Data Centre as part of the function of the National Tidal and Sea Level Facility, hosted by the Proudman Oceanographic Laboratory and funded by DEFRA and the Natural Environment Research Council.

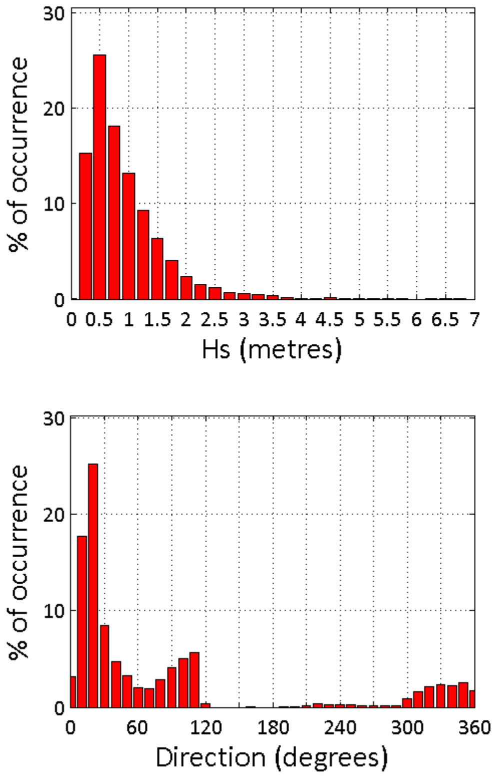

Whitby - Significant Wave Height (Hs) during 2015
metres
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0
5
10
15
20
25
30
Day in month


Storms at Whitby during 2015
Storm threshold is Hs = 3.25m
Hs (m)
7
6
5
4
Missing data
05/02
27/03
16/05
05/07
24/08
13/10
02/12

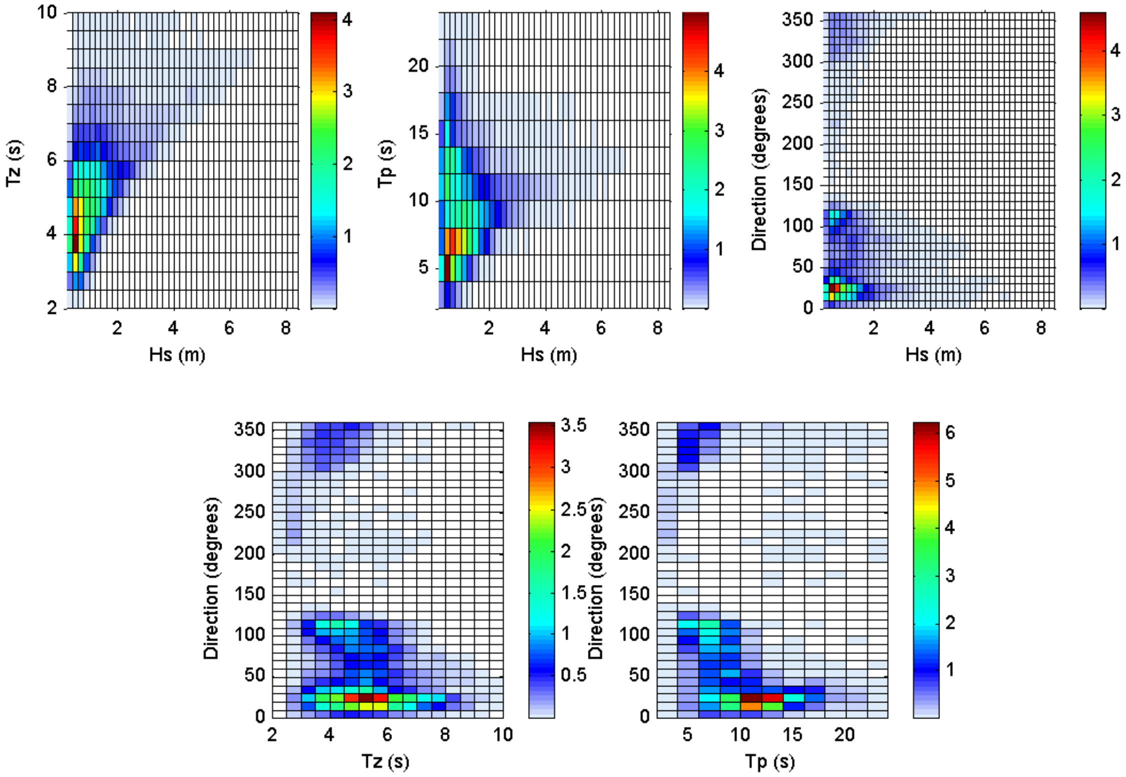

Storms at Whitby - all years
Hs (m)
7
6
5
4
Jan14
Jan15
Jan16
Date

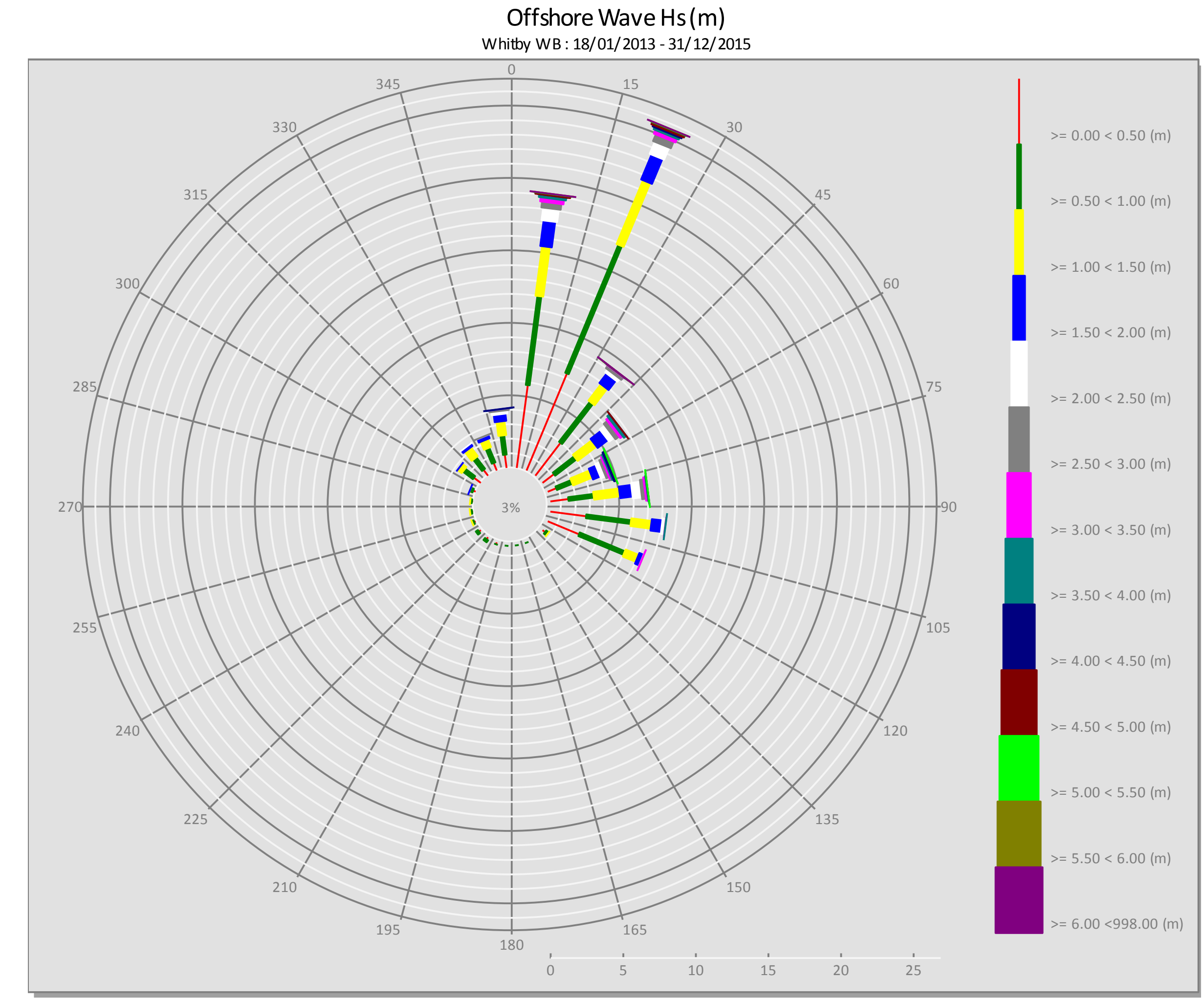

Whitby - Wave height exceedence (Hs)
Wave height (m)
6
4
2
0
2013
2014
2015
Year
0.05%
0.5%
1%
2%
5%
10%

Whitby 2015



Whitby 2013 to 2015 - Joint distribution (% of occurrence)





Offshore Wave Hs (m)
Whitby WB : 18/01/2013 - 31/12/2015
0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
240
255
270
285
300
315
330
345
3%
0
5
10
15
20
25
>= 0.00 < 0.50 (m)
>= 0.50 < 1.00 (m)
>= 1.00 < 1.50 (m)
>= 1.50 < 2.00 (m)
>= 2.00 < 2.50 (m)
>= 2.50 < 3.00 (m)
>= 3.00 < 3.50 (m)
>= 3.50 < 4.00 (m)
>= 4.00 < 4.50 (m)
>= 4.50 < 5.00 (m)
>= 5.00 < 5.50 (m)
>= 5.50 < 6.00 (m)
>= 6.00 <998.00 (m)

Scarborough Directional Waverider Buoy

Location	
OS	509540 E 490003 N
WGS84	*Latitude:* 54° 17.64' N *Longitude:* 00° 19.11' W
Instrument type	
Datawell Directional Waverider Mk III	
Water depth	~19m CD

Buoy in situ off Scarborough beach. Photo courtesy of Fugro EMU Limited

Location of buoy (Google mapping)

Data Quality

Recovery rate (%)	Sample interval
73	30 minutes

Monthly Averages - 2015

All times are GMT

Month	H_s (m)	T_p (s)	T_z (s)	Dir. (°)	SST (°C)	No. of days
January	1.16	9.4	4.6	119	7.2	31
February	1.31	10.1	4.8	68	6.2	28
March	1.01	8.1	4.3	120	6.1	31
April	-	-	-	-	-	0
May	0.65	8.2	4.0	122	9.3	18
June	-	-	-	-	-	0
July	1.39	7.5	5.1	37	12.9	9
August	0.67	6.3	4.0	90	13.3	30
September	1.16	7.2	4.8	70	13.2	30
October	1.03	7.0	4.5	95	13.0	31
November	0.99	7.9	4.1	107	11.3	30
December	1.04	8.3	4.3	99	9.2	30

Storm Analysis

Date/Time	H_s (m)	T_p (s)	T_z (s)	Dir. (°)	Water level elevation* (OD)	Tidal stage (hours re. HW)	Tidal range (m)	Tidal surge* (m)	Max. surge* (m)
21-Nov-2015 07:00	6.70	10.0	8.2	4	-	HW -5	~3.2	-	-
01-Feb-2015 13:00	5.50	10.0	7.5	3	1.44	HW -2	3.1	0.30	0.53
04-Sep-2015 07:30	4.18	10.0	6.6	21	2.77	HW	4.4	0.16	0.25
03-Sep-2015 18:30	3.97	9.1	6.7	10	2.20	HW -1	4.6	0.13	0.33
05-Sep-2015 20:00	3.82	11.1	6.9	16	1.61	HW -1	3.1	0.18	0.34

Annual Statistics

Year	Annual H_s exceedance* (m)						Annual Maximum H_s	
	0.05%	0.5%	1%	2%	5%	10%	Date	A_{max} (m)
2013	-	4.93	4.46	3.76	2.89	2.12	10-Oct-2013 20:30	6.03
2014	3.91	3.16	2.95	2.63	2.22	1.84	14-Oct-2014 04:30	4.45
2015	6.17	4.35	3.57	3.12	2.31	1.81	21-Nov-2015 07:00	6.70

** i.e. 5 % of the H_s values measured in 2013 exceeded 2.89 m*

Distribution plots

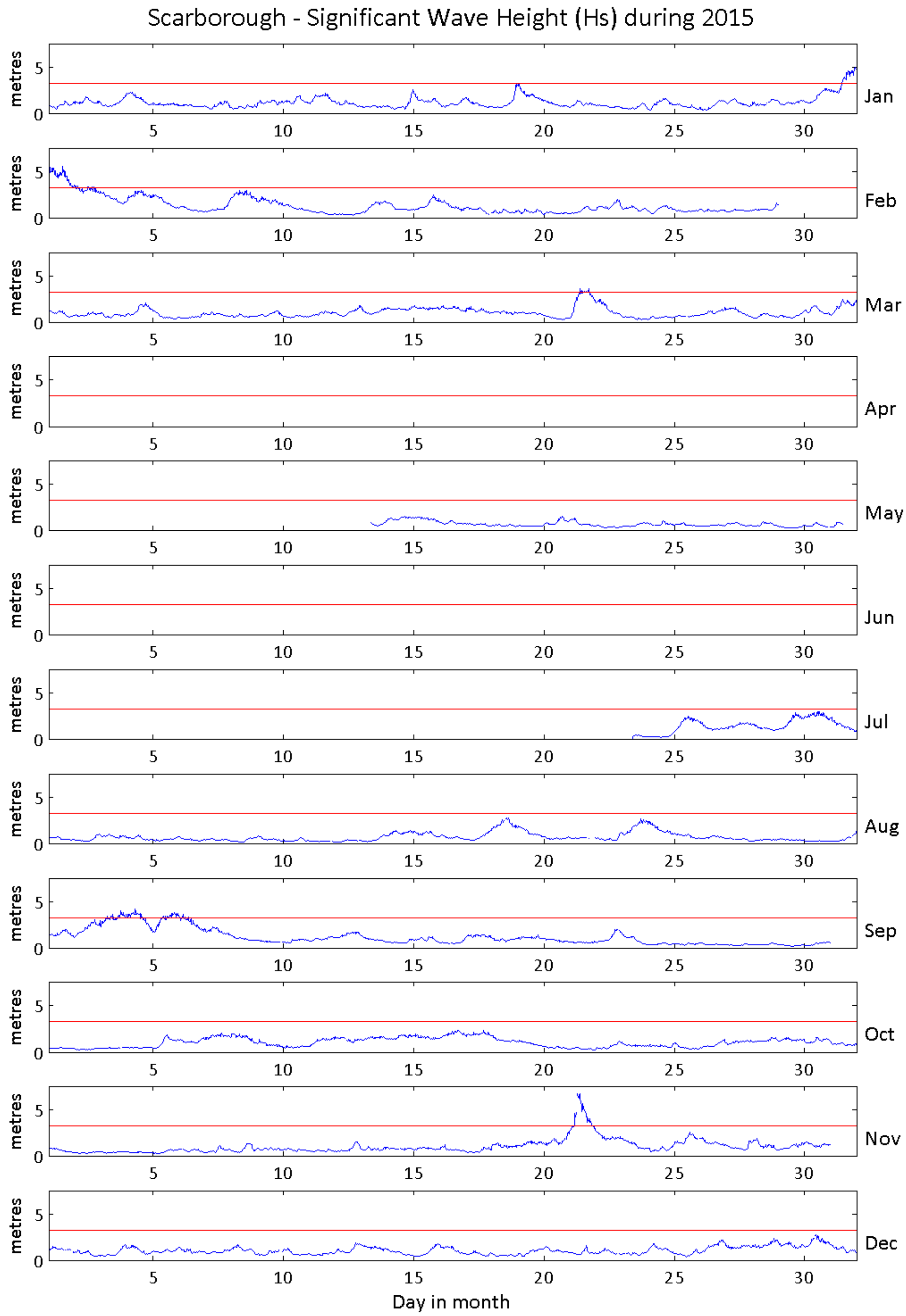
The distribution of wave parameters are shown in the accompanying graphs/tables of:

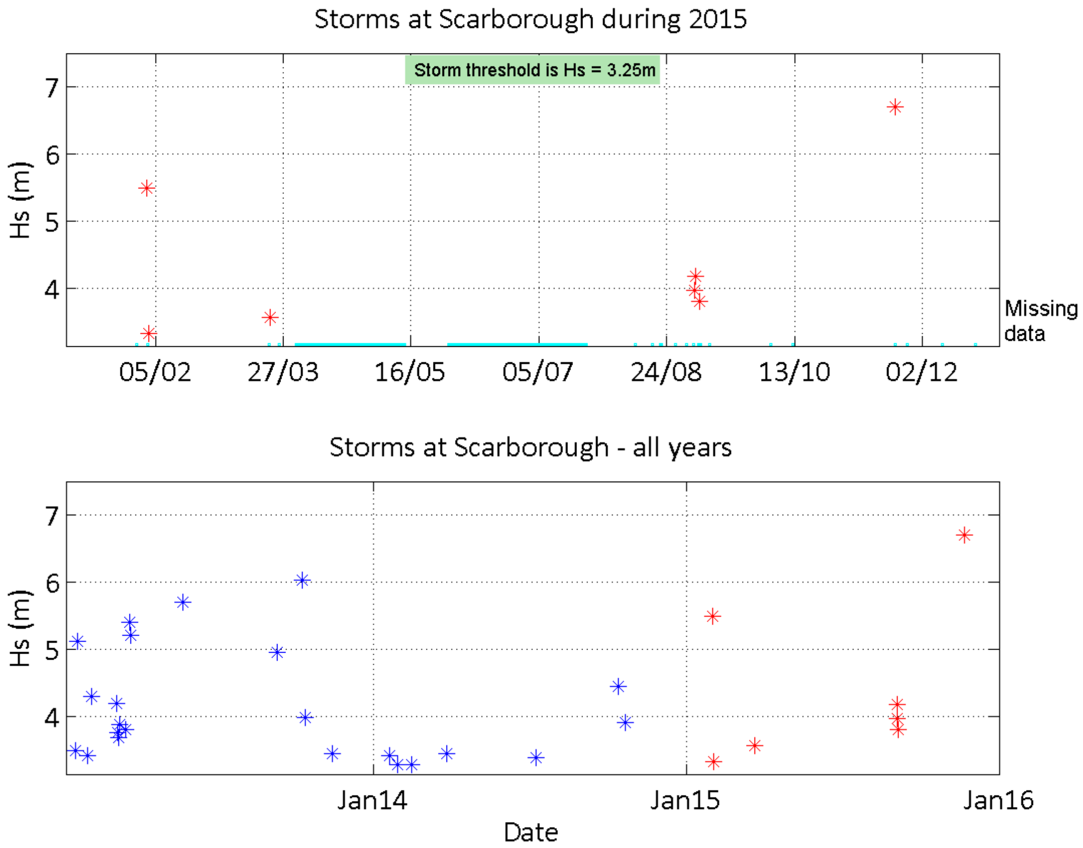
- Annual time series of H_s (red line is 3.25 m storm threshold)
- Incidence of storm waves for 2015. Storm events are defined using the Peaks-over-Threshold method. The highest H_s of each storm event is shown
- Wave height exceedance each year since deployment
- Percentage of occurrence of H_s, T_p, T_z and Direction for 2015
- Joint distribution of all parameters for all measured data, given as percentage of occurrence
- Wave rose (percentage of occurrence of direction vs. H_s) for all measured data

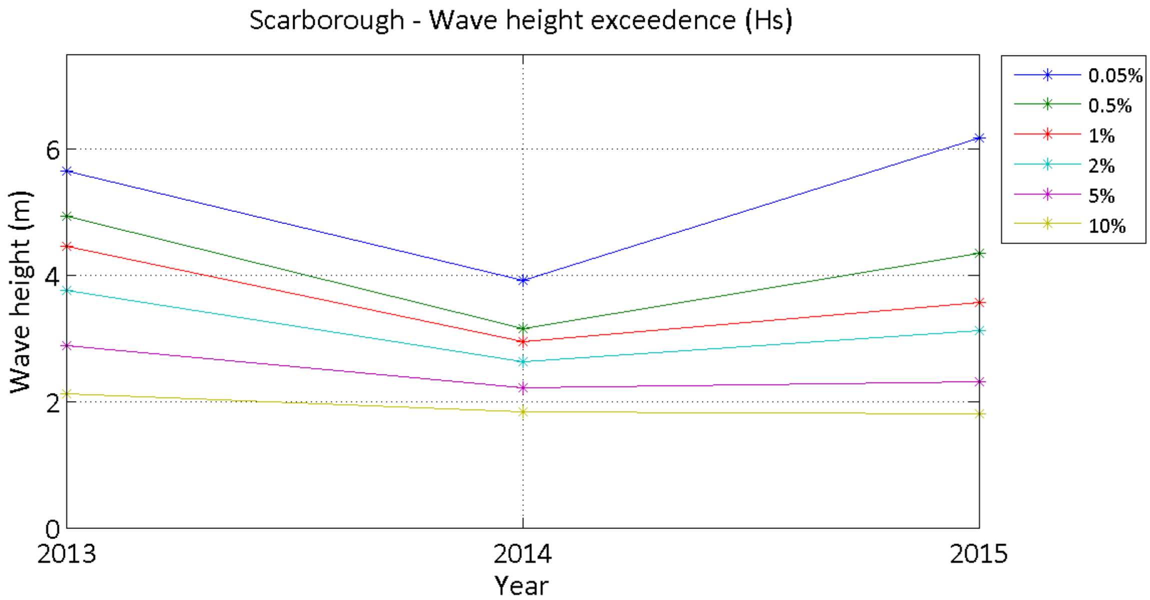
General

The buoy, owned by Scarborough Borough Council, was deployed on 18 January 2013, at which time the magnetic declination at the site was 1.66° west, changing by 0.18° east per year.

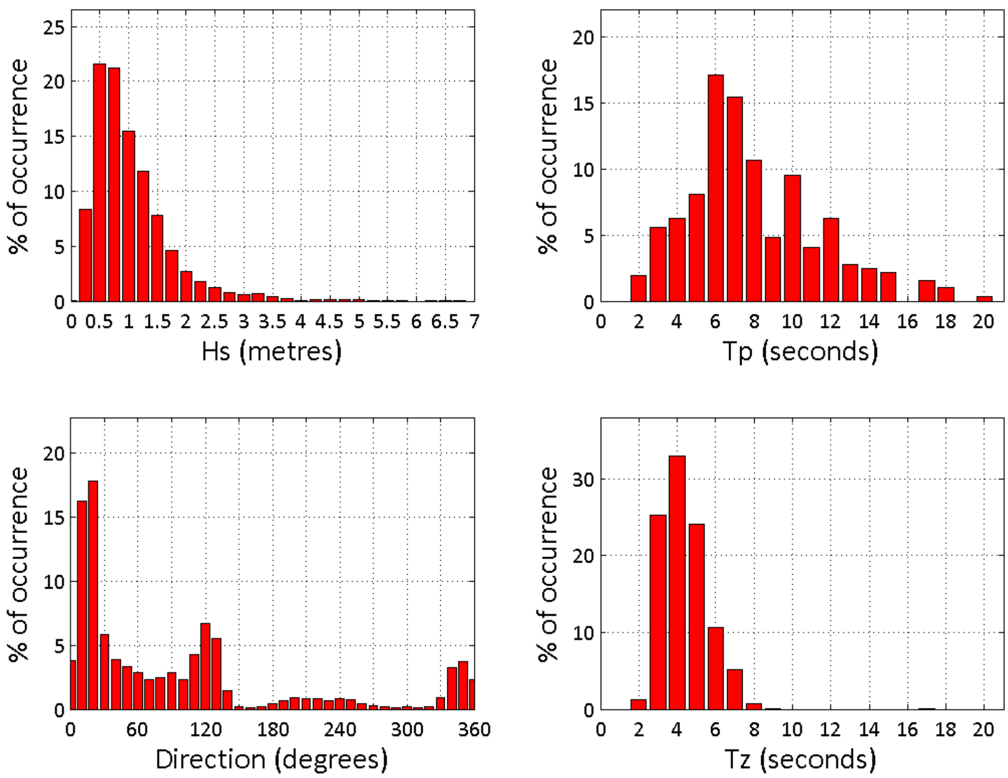
** Tidal information is obtained from the nearest recording tide gauge (the tide gauge at Scarborough). The surge shown is the residual at the time of the highest Hs. The maximum tidal surge is the largest positive surge during the storm event.*


Scarborough - Significant Wave Height (Hs) during 2015
metres
0
5
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
5
10
15
20
25
30
Day in month

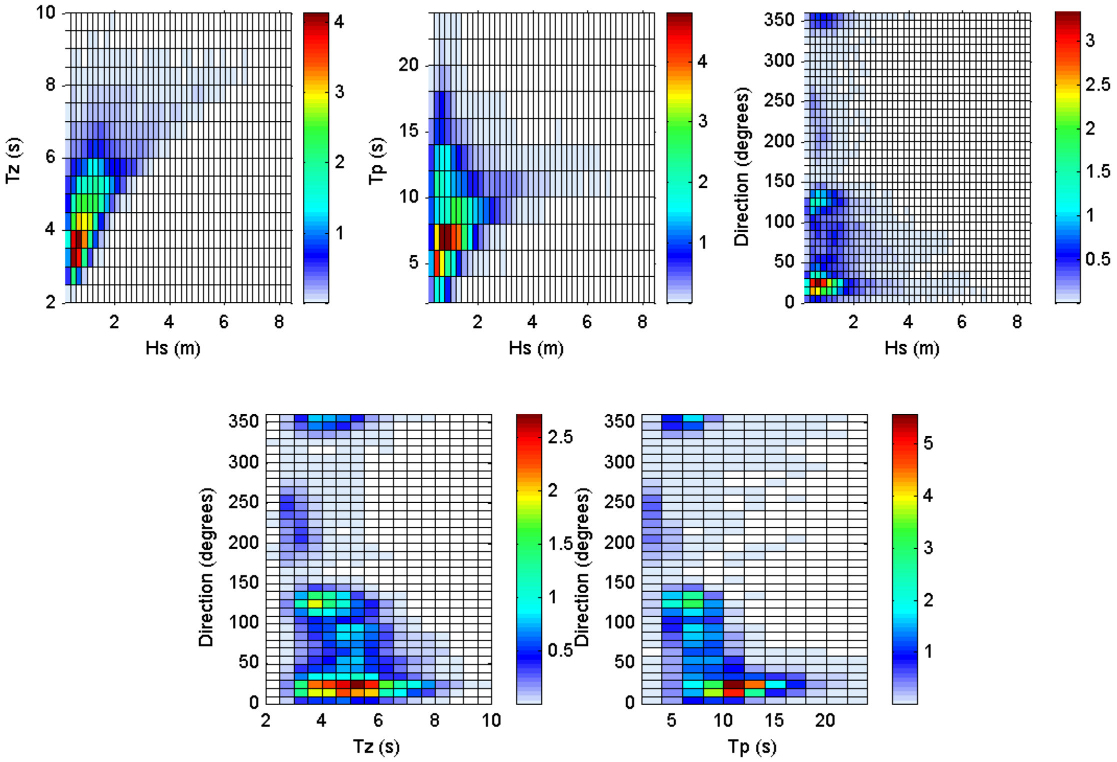

Storms at Scarborough during 2015
Storm threshold is Hs = 3.25m
Hs (m)
7
6
5
4
Missing
data
05/02
27/03
16/05
05/07
24/08
13/10
02/12
Storms at Scarborough - all years
Hs (m)
7
6
5
4
Jan14
Jan15
Jan16
Date

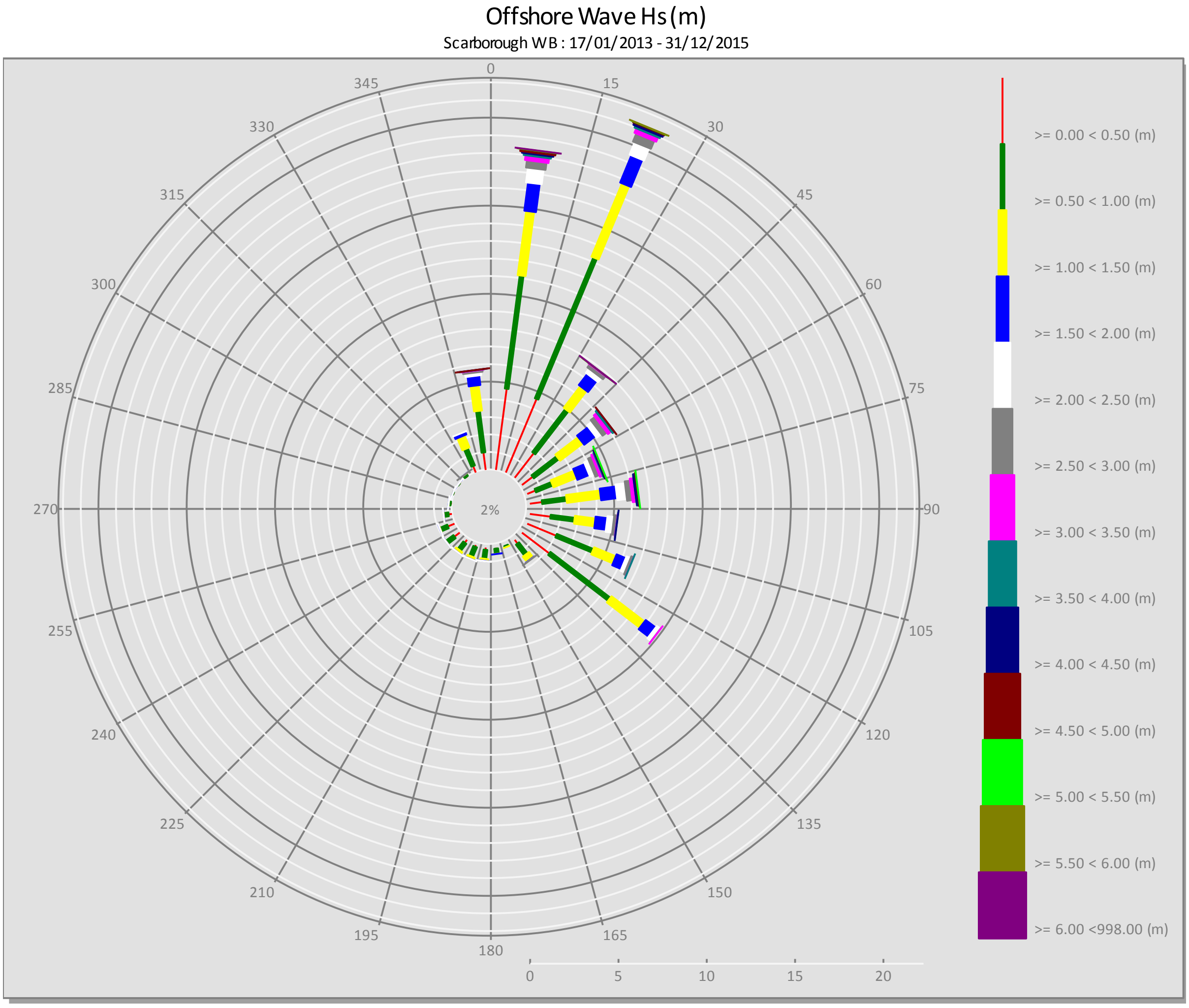

Scarborough - Wave height exceedence (Hs)
Wave height (m)
6
4
2
0
2013
2014
2015
Year
0.05%
0.5%
1%
2%
5%
10%

Scarborough 2015



Scarborough 2013 to 2015 - Joint distribution (% of occurrence)




Offshore Wave Hs (m)
Scarborough WB : 17/01/2013 - 31/12/2015
0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
240
255
270
285
300
315
330
345
2%
0
5
10
15
20
>= 0.00 < 0.50 (m)
>= 0.50 < 1.00 (m)
>= 1.00 < 1.50 (m)
>= 1.50 < 2.00 (m)
>= 2.00 < 2.50 (m)
>= 2.50 < 3.00 (m)
>= 3.00 < 3.50 (m)
>= 3.50 < 4.00 (m)
>= 4.00 < 4.50 (m)
>= 4.50 < 5.00 (m)
>= 5.00 < 5.50 (m)
>= 5.50 < 6.00 (m)
>= 6.00 <998.00 (m)