Wave energy testing in Cornwall: Were the waves during winter 2013/14 exceptional?

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ABSTRACT

Cornwall in the south west UK is an emerging centre for wave energy test facilities at sea, which experienced a series of high profile winter storms during winter 2013/14. This paper presents measurements of these storms in the context of long term statistics for the wave conditions in the region.

The Falmouth Bay Test site (FaBTest) provides an ideal test location for device development, with easy access to a major port, streamlined consenting, and a wave resource combining testing conditions and frequent site access. Wave Hub is situated in a more exposed location off the North Cornwall coast and provides a pre-commercial test bed with 20MW grid connection, again in a pre-consented site. Throughout the development of these projects, the University of Exeter has provided significant resource assessment work to establish the wave and current conditions throughout the region.

Results from these studies are reviewed here, providing an overview of the conditions at the two test sites. In particular, measurements from recent storms are put into context of the long term resource at the sites, including the largest waves ever measured at the FaBTest site.

1 INTRODUCTION

FaBTest is an award-winning, pre-consented, 2.8km^2 test area within Falmouth harbour, Cornwall, UK. It is situated between three and five kilometres offshore in water depths of 20m-50m with seabed types of rock, gravel and sand. The wave climate and proximity to port facilities offer regular access, whilst still providing testing physical conditions for demonstration. As such, the site provides a fast, flexible, low risk and low cost solution for the testing of marine energy technologies, components, moorings and deployment procedures.

The Site is leased from The Crown Estate and has a Marine Consent for testing, subject to permits issued by Falmouth Harbour Commissioners. Operational support of the site, as well as ongoing monitoring and world leading research is provided by the Renewable Energy Group from the University of Exeter, based on the nearby Penryn campus, made possible in part thanks to an investment of Regional Growth Fund money. The RGF investment of £549,000 into FaBTest was approved by the Cornwall and Isles of Scilly Local Enterprise Partnership (LEP). The LEP recognised FaBTest as a key investment priority and a unique asset which can create economic benefits and market opportunities. The Regional Growth Fund is managed locally by Cornwall Development Company on behalf of the LEP and Cornwall Council.

FaBTest characteristics:

- Within Falmouth Port limits
- 4.5 km from Falmouth Harbour entrance
- 7.5 km from dock area
- In the lee of the Lizard Peninsula (sheltered from the prevailing SW wind and swell)
- Exposed to waves from the E - SE (long fetch)
- Peak tide height range ~6.0 m
- Peak tidal surface current ~ 0.8 m/s
- Adjacent to extensive dock facilities incorporating three dry docks, wharf space, cranage and a heavy load out quay

- Access to an Experienced supply chain, with an impressive track record in delivering marine renewable projects
- Support from world leading research by the University of Exeter

FaBTest itself is situated to the east of the Lizard Peninsula. This landmass shelters the site from the prevailing westerly waves that characterise the climate in the region. Large storm waves, swells, and waves with a South Westerly direction will refract around the peninsula to impact the site, providing regular low frequency events. The site is directly exposed to the South and East, although fetch is limited by the south coast of England and the North coast of France (fig. 1).

As such, the wave climate at the site is a combination of low frequency waves from the South, with wind waves and occasional storms from the South and East. This situation means that the site is regularly calm, giving good access for marine operations, whilst experiencing severe conditions suitable for demonstrating devices and components up to full scale.

Testing at site is supported by the applied Offshore Renewable Energy (ORE) research group at the University of Exeter. This group provides continuous measurement of the waves at site as well as currents, with wind measurements in development. This work runs alongside monitoring of devices and mooring systems to support testing for devices on site. Research within the group is targeted at developing best practice for classifying the physical conditions on site and relating these to device measurements. The outcome is valuable support to developers wishing to optimise the lessons learnt during the test phase and continuous development of best practice for demonstrating marine energy projects at sea.

During the winter 2013/2014 a series of very large storms impacted the UK. This led to widespread coastal flooding, destruction of coastal infrastructure and widespread damage to floating assets such as buoys. Fred Olsen Renewables had the Bolt II device operating at the FaBTest site, supported by wave measurements. All infrastructure survived with little or no damage. However, the waves experienced offered a different level of conditions to those previously encountered at site, including the highest wave measured to date, approaching 10m (H_{m0} = 5.9m).

In response to the high profile nature of these storms and the obvious damage that they caused, this paper puts them into context with the available historical data. In doing so it is possible to understand where they fall in the range of extreme conditions predicted for the site. The work re-visits extensive research applied to characterise the physical conditions at the FaBTest site. In particular, measurements taken during the storms are related to predictions of extreme wave heights from a 23 year hindcast model developed by the ORE group [1].

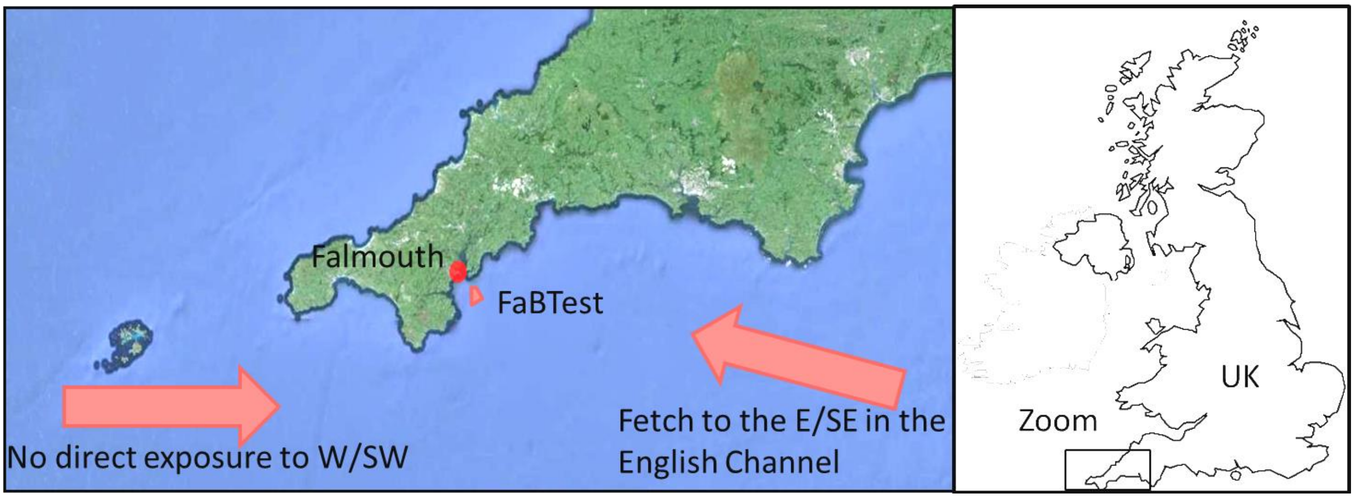

Figure 1. The location and exposure of the FaBTest wave energy site in the UK, showing its exposure and location relative to the port of Falmouth. Image courtesy of Google Earth. Landsat image, data SIO, NOAA, US Navy, NGA, GEBCO

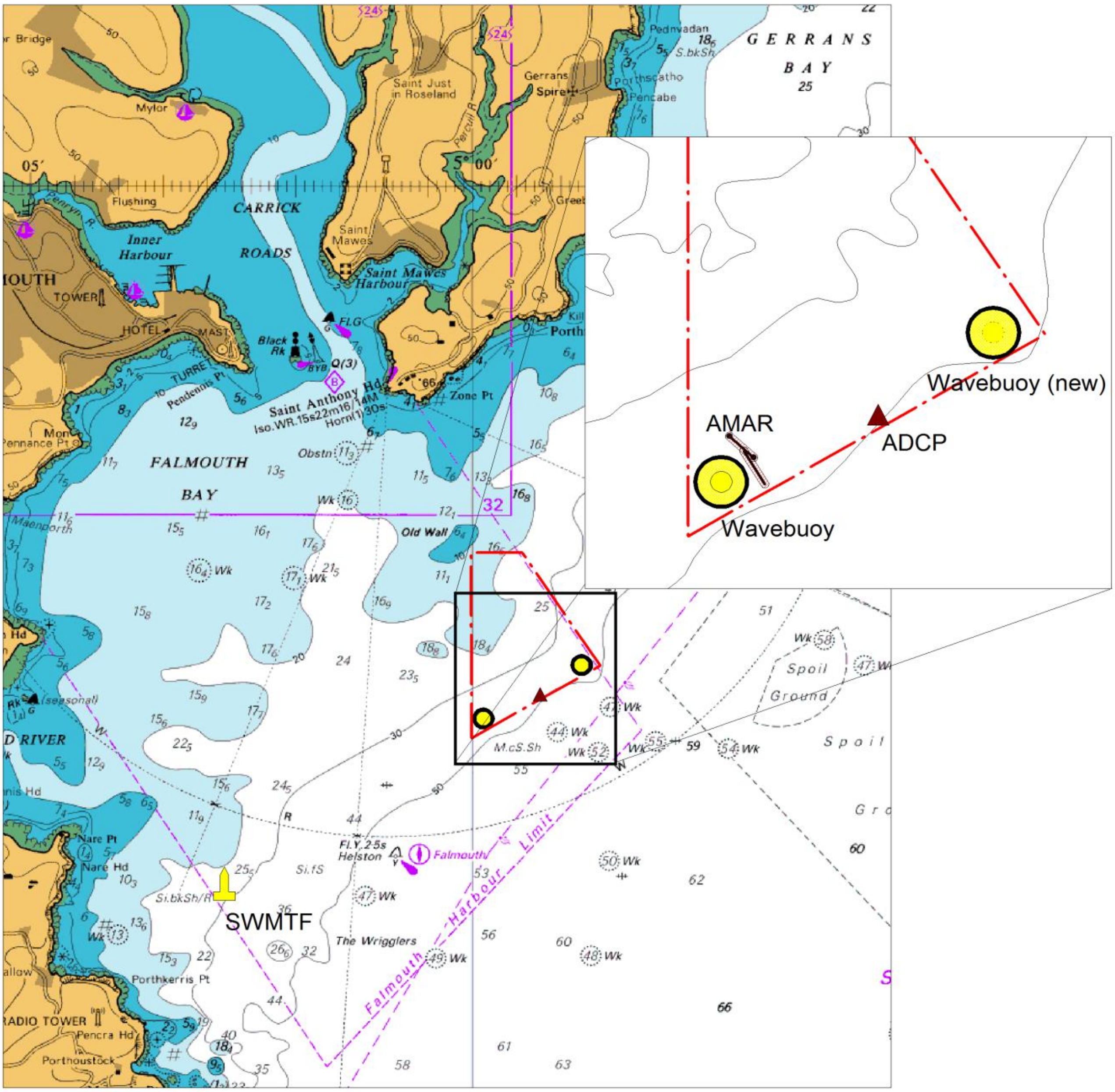

Figure 2. Measurement locations within the FaBTest site, including the excursion zone for wave buoys on their moorings. Map courtesy of UKHO.

The availability of in situ measurements offers an opportunity to assess the accuracy with which the regional model is able to predict conditions during these extreme events, which are amongst the most important considerations for marine energy testing.

1.1 DATA COLLECTION

Data collection at the FaBTest site provides in situ data of the physical environment, supported by modelling and includes,

- Directional wave buoy stationed permanently within the site, in 40m depth since March 2012 (fig. 2).
- Second wave buoy being delivered to provide options for reducing spatial separation between measurement and devices, and monitoring spatial variability in waves across the site (Initial deployment location marked fig. 2).

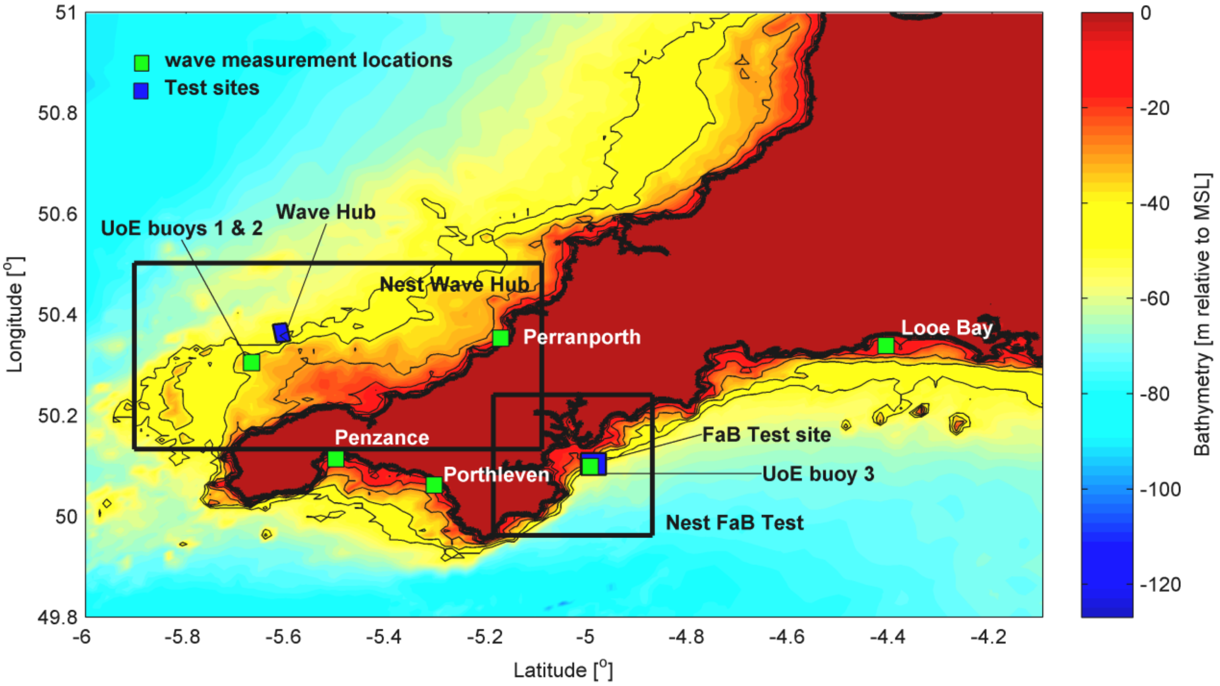

Figure 3. Model domain for the regional wave model (from [1]).

- High resolution coastal wave model with very high resolution coverage of the FaBTest site itself, provides 23 year hindcast of conditions, validated against local measurements (fig. 3).
- Measured tidal current profiles from ADCP.
- Direct links to complementary research and development streams, including the South West Mooring Test facility, The Dynamic Marine Component Test facility, acoustic monitoring, and other environmental impact monitoring.

The Offshore Renewable Energy group have a demonstrated strength in applied research to support offshore energy technology development. Within this team, there has been an historic strength in resource assessment, particularly for wave energy The group were instrumental in developing standards for the measurement, processing and analysis of wave data for the assessment of wave energy devices [2].

Initiated in support of the Wave Hub, the University of Exeter developed a regional wave model using the coastal wave model SWAN. This high resolution model provides wave parameters across the region, with very high resolution nested grids covering the FaBTest site. The model has been run in hindcast mode to provide a very high quality data set spanning 23 years of historic data.

The wave model is validated by a campaign of in-situ measurements across the region [1] and the combined datasets provide a valuable high-quality resource for assessing the oceanographic conditions across the region.

In particular, the wave model has been applied to the definition and characterisation of the wave conditions at the FaBTest site, providing valuable information for site developers. A directional wave buoy has been operational on site since March 2012 (fig. 2). This returns wave parameters every 30 minutes as well as measuring the surface position of the buoy at a frequency of 2Hz. Data retrieved are of very high quality and the time scale of two years provides a wide range of measured conditions including significant storms during the winter 2013/2014.

The data collected are underpinned by ongoing research and development into the characterisation of the physical environmental conditions, and the assessment or prediction of device performance in that environment. This research has direct relevance to resource assessments, to the demonstration of device performance and to impact assessments. As such, it contributes to the continued development of best practice for marine energy industries [4,5,6].

A further wave buoy has been purchased to consolidate the program of long term monitoring (fig. 2). This will also offer the possibility of real time wave monitoring, reduced separation between measurement location and device during testing and support research into spatial variations in waves across the site. This added flexibility could incorporate particular needs for developers, or will support short term research projects where intensive data collection is required (e.g.[4]).

ADCP units measure the current through the water column, providing a profile of current speed and direction. These have been deployed at the FaBTest site to characterise the current regime at the site and further measurements are being planned. Real time communication is in development although the nature of the site and the instrumentation make this a difficult proposition, albeit with significant potential benefits to device monitoring at site.

4.1 Wave Buoys

Two directional wave buoys are available to the FaBTest site. These buoys are designed to follow the sea surface motion. Therefore, measuring the buoy motion provides an exact measurement of the water surface, which can be used in turn to derive a directional measurement of the surface wave field.

Data presented here has been captured by the Seawatch mini II (SWM). This is a commercially available wave buoy built by Fugro Oceanor. Accelerations are sampled using solid-state accelerometers on three separate axes. When combined with simultaneous heading and tilt readings, accelerations are resolved to heave (vertical), east and north axes. These are then double-integrated to give a time-series of positions on these three axes from which a wave spectrum and summary parameters are calculated. A description of this process is available in the instrument manual [7].

Processing is performed on board the buoy, although for this research the summary parameters have been re-analysed from the raw data in order to avoid the unwanted influence of spectral filters applied on board [8]. Subsequently, during archiving, detailed quality control has been performed, again following a procedure laid out in [8].

1.2 WAVE MODEL

This study used the spectral wave model SWAN (Simulating WAves Nearshore) [9], run across a high resolution grid, to predict the sea state variability over the buoy array site. SWAN accounts for depth and current-induced refraction and represents processes that generate, dissipate or redistribute wave energy. These processes are represented within SWAN as source terms, which are quantified by their effect on the spectral energy values. Processes represented include the deep water processes of wind input, whitecapping dissipation, quadruplet nonlinear interaction and the depth-limited processes of bottom friction dissipation, depth-induced breaking and triad wave-wave interactions. User-induced source terms can also be applied including vegetation, or obstacles introduced to the model domain.

The regional model, covers the area from 4 to 7 degrees west and 49 to 51 degrees north at a grid resolution of 1 km x 1 km (fig. 3). Within this, a 100m resolution nest covers the area surrounding the FaBTest site. The hindcast used default SWAN parameterizations for wind, quadruplet wave-wave interactions, bottom friction dissipation, depth-induced breaking and triad wave-wave interactions. For whitecapping the formulation settings proposed by Rogers et al. [10] were used. The hindcast set-up is described in more detail in [1].

The bathymetry for the wider model and the 100m nest was constructed from data interpolated from Marine DigiMap [11].

Two hindcasts were available for this study. For the first, wave and wind input was provided by the European Centre for Medium-Range Weather Forecasting (ECMWF) through the global wave hindcast ERA-interim, utilising the WAM wave model. This hindcast covers approximately 23 years between 1 January 1989 and 1 November 2011 with a time step of 60 minutes full details are provided in [1]

A second hindcast used spectral wave data as boundary conditions, reconstructed from partitioned data from the UK Met Office's 12km resolution North Atlantic European model [12]. Wind conditions across the grid were also supplied by the Met Office model output. This model was limited to 8 years of hindcast due to data availability. As such it was not used for extreme analysis.

1.3 EXTREME ANALYSIS

Two separate studies predicting the return values for significant wave height have been conducted for the FaBTest site. Initial work fitted modelled wave heights to a Fisher-Tippett 1 (FT) distribution [13].

This work highlighted the existence of a tail in the data. The fit can be improved using an extra parameter, such as the Weibull 3 parameter, or through application of a peaks over threshold (POT) method, as recommended by the IAHR [14]. Subsequent work fitted exceedances over a threshold to a generalised Pareto distribution (GPD), with function,.

$$F(x;k,\sigma) = 1 - \left(1 + \frac{kx}{\sigma}\right)^{1/k} \text{ if } k \neq 0$$

$$F(x;k,\sigma) = 1 - e^{-x/\sigma} \text{ if } k = 0$$

with scale parameter σ and shape parameter k. Threshold choice for FaBTest was 3.15m. For further details, the reader is directed to [1].

Both of these procedures were repeated here using the WAFO toolbox [15] for the 23yr model hindcast of significant wave heights at the FaBTest site. Model fits were estimated by a least squares method (for FT1) and a probability weighted moments method (for GPD). Data were plotted on axes such that data fitting each model would fall on a straight line. Return values for the significant wave heights were calculated through extrapolating the fitted models to the probability that a level *R* is exceeded during a period *T*, expressed in years.

$$P(H_S > R_N) = 1 - F(R_N)$$

Where,

$$F(R_N) = 1\text{-}1/\text{N}$$

These data were then compared to the measurements made at site during the storms of 2013/2014

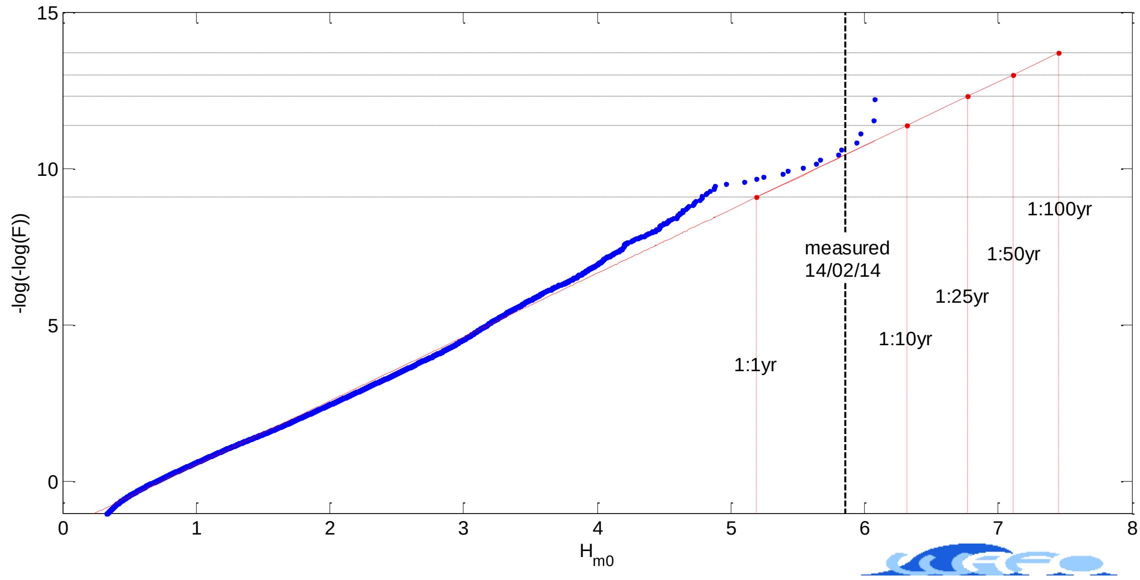

Figure 4. Modelled wave heights for the FaBTest site (Blue dots) and a fitted Gumbel distribution (red line). Return values estimated through extrapolation of the model are plotted with vertical red dashed lines. Also shown is the largest significant wave height measured during the 2013/2014 storms as a vertical black dashed line.

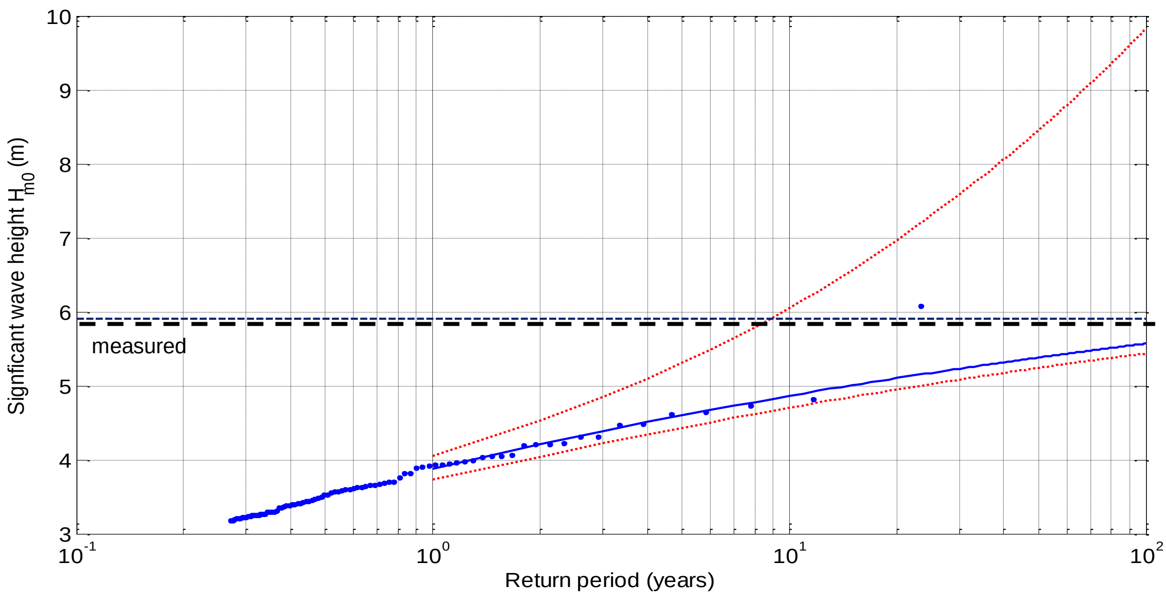

Figure 5. Predicted return values for the FaBTest site from model data (Blue dots, extrapolated using a GPD distribution (blue line). Red dotted lines represent the 95% confidence intervals calculated using the profile likelihood method [REF WAFO]. Also shown is the largest significant wave height measured during the 2013/2014 storms as a horizontal dashed line.

2 RESULTS

The maximum measured wave height at the FaBTest site, $max(H_{meas}) = 5.9$m on Feb 14th 2014. (fig. 4 & 5). A large depression moved slowly NW towards the British Isles. Strong South Westerly winds occurred over significant fetch, creating large south westerly swell. Arriving on the Cornish Peninsular with storm force southerly winds, storm waves generated in the relatively short southerly fetch combined with swell refracting around the Lizard peninsular to the west of the site to create the largest waves measured on site. It was a combination of the strength of the local winds and the southerly angle to the fetch in the North Atlantic that made this event extraordinary. Storms with similar intensity and offshore wave heights that exhibit a more westerly angle of wave approach refract less energy into the site (fig. 1).This event has similarities to that of December 17th 1989, when the maximum model predicted significant wave height, $max(H_{mod}) = 6.1$m would have occurred at site. This is the only storm in the hindcast where $max(H_{mod})>.max(H_{meas})$. At this stage model data is not available for the period 2013/14 for a direct comparison between model and measurements for the 2013/14 storms.

Significant wave height return values, derived for the site from a GPD POT method, based on the regional SWAN model forced by ECMWF data, were compared to the measured data;

- $max(H_{meas})>R_{100}$ by 30cm (fig. 5).
- In 20 months of site data, $H_{meas} >R_1$ during 5 separate storm events.

These occurrences are within the error bounds of the return value predictions.

Significant wave height return values, derived for the site from an FT1 extrapolation method, based on the same data provides the following results;

- $max(H_{meas})<R_{10}$ (fig. 4).
- H_{meas} has never exceeded R_{10} during the 25 years of data

For the period available where the regional SWAN model was forced by MetOffice data, predicted greater wave heights were greater than the equivalent in the ECMWF forced model (fig. 6). In this data set, R_{100} calculated from the ECMWF forced model is exceeded regularly during the 8 year period.

Mean wave direction for the storm that created $max(H_{meas})$ was from a southerly direction. Both models suggest that it is waves from this direction that will cause the most extreme events. Extreme wave heights have also been incident from the South East where a relatively limited fetch exists in the English Channel. The significant wave heights measured from this sector $max(H_{meas})[SE] = 4.3$m during 11/03/13.

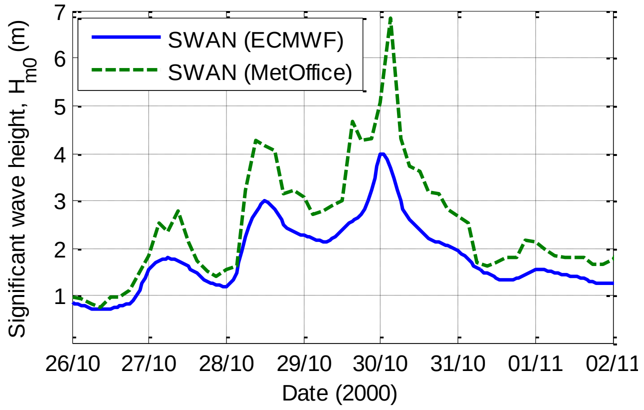

Figure 6. Comparison of significant wave height data for a storm during October 2000 where significant disparity exists between data from the ECMWF forced model and the MetOffice forced model.

This significantly exceeds the maximum predicted by the ECMWF forced model during the 23 year hindcast, $max(H_{mod})[SE] = 3.9$m.

During 2012/2013 there was a prevalence of easterly and south easterly wave systems incident on site. Measured data exceeded wave heights for storms from this direction through the whole of the 23 year hindcast model. Across all records, the ECMWF forced model hindcast has a relatively small proportion of energy arriving from the SE sector when compared to both the MetOffice forced hindcast and the measured data (fig. 7). In the measured data, a secondary peak in the empirical distribution occurs at a SE direction. This is significantly larger in the measured data, perhaps due to the short time scale. However, the directional location of the peak is most closely matched by the Met Office data set.

3 DISCUSSION

The title of this paper poses the question: *Wave energy testing in Cornwall: Were the waves during winter 2013/14 exceptional?*. The answer is yes, they were exceptional. In the 23 year record, the model hindcast estimates that only one storm exceeded the measurements taken on 14/02/14, with the previous storm during the $16^{th}/17^{th}$ December 1989. The conditions measured exceeded R_{100}, the value expected to be exceeded every 100 year, when derived using the longest available data set, and recommended POT methodology, (fig 5). The measured wave heights were within R_{10} for the more conservative FT1 extrapolation (fig. 4). As such, they would not have exceeded the design characteristics for engineering projects at site using this methodology. However, comparison with the alternative SWAN model, forced by the higher resolution MetOffice 12km resolution North Atlantic European model, and the in-situ measurements themselves, supports previous indications that the ECMWF data may be underestimating extremes at site [1].

For locations such as FaBTest, the prediction of extreme events will be highly dependent on the ability of relevant wave models to resolve the interaction of waves and local landmasses and associated physical processes affecting the waves. The closer match in directional properties between the model output when forced by the MetOffice data and measured data highlights how input data could improve accuracy of the regional SWAN model (fig. 7). At this stage, a possible underestimation in the model data must be taken into account when deriving design characteristics for FaBtest. One conclusion may be that it is prudent to adopt results from the more conservative FT1 approach than the POT. However, there is some deviation in the fit at the upper tail, giving an indication that the longer return values are conservative estimates. This will potentially increase costs for those operating at site unnecessarily.

The results presented here have shown the importance of detailed regional modelling and in-situ data to the accurate prediction of extremes and other site information. The resources available at the FaBtest site, and the research support from the University of Exeter, offer an excellent resource for marine energy development.

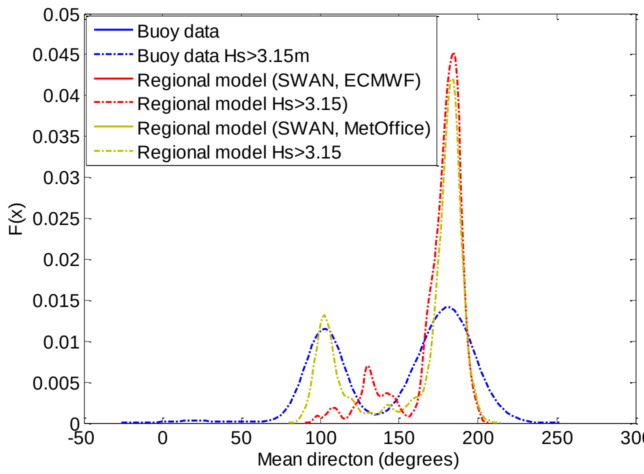

Figure 7. Comparison of the empirical distribution of mean wave direction (m_{dir}) between models and measured data.

Monitoring through the storms of 2013/14 has sharpened the focus on the fact that further refinement of the modelling process has the potential to improve the sensitivity of extreme assessments. Ongoing work is further developing the regional wave model, bringing it up to date to provide a direct comparison with in-situ data through the winter period. Research is also underway into improving the representation of tidal flows in the wave model, as well as continued gathering of in-situ data. Through this work, the University of Exeter, and collaborators throughout the region, continue to ensure optimum support for developers operating at FaBTest and throughout the South West UK.

ACKNOWLEDGMENTS

Funding from the Regional Growth Fund (RGF) has supported development of an active plan of in-situ monitoring and model development, improving the environmental and hydrodynamic data available to FaBTest and within the region. Also supported has been research into developing advanced processing to provide a valuable data source that allows developers to optimise planning and operation of device testing using the regions marine energy test sites. This has been complemented by funding from the NERC Flowbec project which has advanced the classification of the physical environment by supporting research into more refined analysis techniques.

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