COMPARISON OF THE PERFORMANCE OF THE METOFFICE UK-WATERS WAVE MODEL WITH A NETWORK OF SHALLOW WATER MOORED BUOY DATA

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1. INTRODUCTION

The design and management of most coastal engineering- and operational shoreline management schemes, within the UK, has relied historically upon hindcast synthetic wave data and numerical models of wave transformations, to provide wave climate design conditions and operational management data. Such data sets are occasionally supplemented with short time series of localized wave data but hitherto there has been no systematic shallow water wave measurement programme off the UK coast. Some long-term buoy measurements are available for sites on the UK shelf, but these are all in deep-water conditions.

Concerns have been expressed however, that numerical modelling approaches may not be sufficiently robust to provide wave conditions with adequate accuracy for design and management purposes at some shallow water sites, particularly where the bathymetry is complex. Particular concerns have been raised with respect to the adequacy of directional synthetic wave data, used to drive highly sensitive beach plan shape models. Similarly, high quality wave data is needed to assess the validity of cross-shore empirical models, used for structure stability and overtopping calculations. Recent analyses of the traditionally used JONSWAP formulation suggest that this under-predicts wave heights for some short-fetch conditions, in high wind conditions. Although modifications to the formulation have been suggested these have not been validated in full-scale measurements.

The Southeast Strategic Regional Coastal Monitoring Programme (Bradbury *et al*, 2002) is a recently developed operational, long-term, large-scale regional coastal monitoring programme that includes a network of directional wave rider buoys (Figure 1) to supplement the supply of synthetic hydrodynamic data along the southeast of England. The wave buoys sites are all at shallow water locations. Wave measurements are therefore located in a zone where these are rarely made on a strategic basis. The buoy network has been established on a strategic regional basis, but with some focus on locations where high expenditure is needed to provide beach management schemes, for protection against coastal flooding or erosion. Further, the network also provides an opportunity to examine selected sites where wave transformation modelling is unreliable or very complex.The monitoring programme also includes a wide range of other measurements of coastal change, at a range of temporal and physical scales; these include measurements of: tides, beach profiles, bathymetry, LIDAR and aerial surveys. These measurements are used in parallel with the wave data, to provide predictive and analytical tools for operational and strategic shoreline management

The principle aims of the new hydrodynamic network are: to generate characteristic wave climates for future coastal defence design considerations; to validate wave transformation models, particularly in areas of irregular bathymetry; to produce data for performance evaluation of coastal engineering and beach management projects and to produce high quality time series of tidal elevation to predict extreme water levels at the coast. The programme provides freely available archive and real time data at a range of temporal and spatial scales.

The comparisons made in this paper are intended to highlight circumstances where the hindcasting techniques appear to be robust, and also to identify where further model development would be beneficial, for specific applications in shoreline management. It is recognized that the observations are made in particularly challenging conditions, at the landward limits of the model boundary. The review is a collaborative initiative between model end users (Channel Coastal Observatory) and the developers (UK Met Office). The paper presents an overview of coastal engineering requirements for wave data, examining applications for a range of temporal and spatial scales.

2. DATA SOURCES

2.1 Directional shallow water moored buoy network

A strategic network of moored directional wave rider buoys has been established (Figure 1) along the coast of southeast England. A number of other wave measurement sites, including pressure recorders, wave radar and step gauges are also included within the network. The moored wave buoy network sites are all located in shallow water (typically 10-12mCD). Tidal range on spring tides at these sites is highly variable ranging from about 1m in the central English Channel to 8m at the eastern end of the channel (Table1).

Regional wave climates are compiled routinely, within the regional coastal monitoring programme, for each of the sites, to inform large-scale strategic decision-making across 1000km of coastline.

2.2 Real time data and applications

Summary integrated key parameter data (H_s, T_z, □) are available for operational management at local sites via the project website (www.channelcoast.org), in near real time. Wave data is updated every 30 minutes and tidal elevations every 10 minutes. The programme provides measurements of integrated parameters within 1-3km off the coast. Quality controlled archive data are also available freely; these include summary integrated parameters and also full spectral data sets for the wave buoys.

Advances in web technology have opened up new applications for such easily accessible measured wave and tidal data, to inform emergency coastal management decisions and operational coastal engineering. Operational use is made of the data by provision of automated text message alerts to operations engineers, when defined threshold parameters are exceeded. Web-delivery of hydrodynamic parameters is used for strategic and operational coastal engineering and flood warning. Applications of the real time data include operational flood management, planning rapid response surveys for storm events and support for marine based construction phase operations, for instance in delivery of rock armour, using marine based plant.

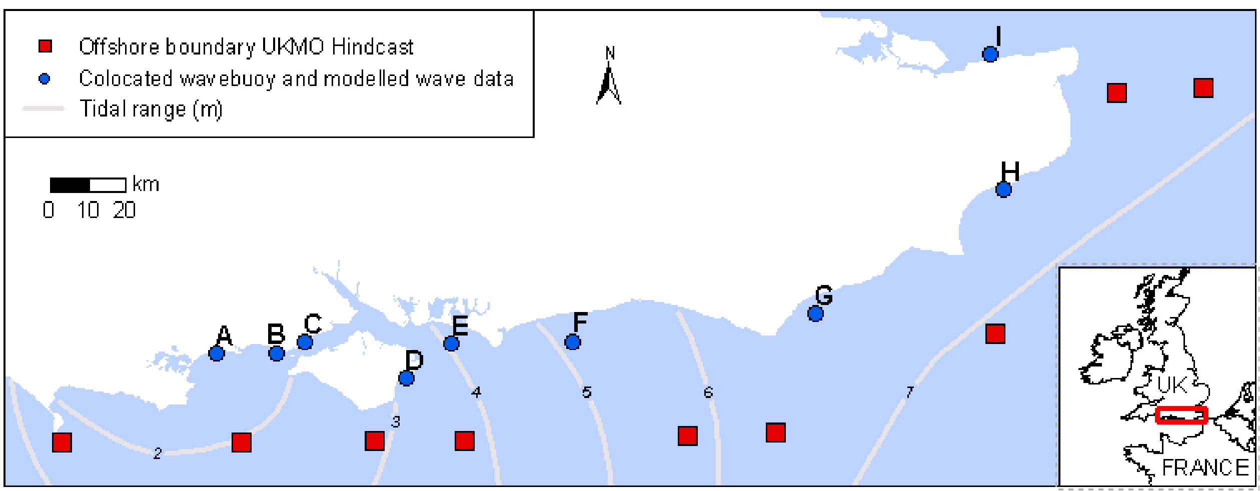


Figure 1 Location of Southeast England wave measurement sites

Location		Position	Recorder type (DWR= Datawell MkIII directional buoy)	Record length (all recorders ongoing)	Water depth (mCD)	Tidal range (m)
Boscombe	A	50°42.68'N 1°50.376' W	DWR	Jul 2003-Jul 2004	10.4	2
Milford-on-Sea	B	50°42' 73"N 1°36' 93" W	Non-directional DWR	Jun 1996-Jul 2004	11	2.2
Lymington	C	50°44' 25"N 1°30' 25.6" W	Valeport 730D Pressure	Jun 1996-Jul 2004	5	3.1
Sandown Bay	D	50°39.02'N 01°07.75'W	DWR	Jun 1996-Jul 2004	10.7	3
Hayling Island	E	50°43.99'N 00°57.55'W	DWR	Jun 1996-Jul 2004	10.2	5
Rustington	F	50°44.03'N 00°29.67'W	DWR	Jun 1996-Jul 2004	9.9	6
Pevensey Bay	G	50°47'0.2"N 00°25'1.5"E	DWR	Jun 1996-Jul 2004	9.8	7
Folkestone	H	51°03.53'N 01°08.29'E	DWR	Jul 2003-Jul 2004	12.7	8
Herne Bay	I		Etrometa step gauge		8	6

Table 1 Wave recorder locations and type

2.2 UK Met office wave models

For many years the UK Met Office (UKMO) has run second-generation global and regional wave models to provide forecasts of sea state, supporting a range of user applications. The sea state at any point may be thought of as the sum of many individual waves, each of a particular direction and frequency. This can be represented as the wave energy spectrum, where the wave energy in each frequency and each direction is known (Bidlot *et al*, 1999). The Met Office wave model divides the wave energy spectrum at each grid point into 13 frequency components and 16 direction components. The lowest model frequency is at 0.04 Hz (25 seconds period or 975 m wavelength), and the highest frequency resolved by the model is 0.324 Hz (three seconds period or 15 m wavelength). The effect of waves at higher frequencies is included in the calculation of source terms.

The wave models account for growth of waves due to wind input, dissipation of energy by breaking waves, and transfer of energy between spectral components by non-linear interactions. Wave energy is advected from one grid point to the next at the group velocity. The wave models are run using hourly surface winds from global and mesoscale numerical weather prediction (NWP) models and there are three operational wave model configurations, with different areas and resolutions, currently in use (global, European and for UK waters). All the models include some shallow-water physics, namely bottom friction, refraction and shoaling. The UK waters model additionally includes the effects of time-varying currents on the waves. The global wave model assimilates wave height data from the radar altimeter on the ERS-2 satellite.

2.2.1 European wave model

The European wave model covers the area from 30.75° N to 67° N and 14.46° W to 41.14° E, with a resolution of approximately 35 km. The European wave model is run twice daily from 00 UTC and 12 UTC data times and provides forecasts out to five days ahead, using hourly NWP forecast winds. The model takes boundary data from the global wave model at the open boundaries, allowing swell from the Atlantic to propagate in. Complete time series records of the model integrated parameters output have provided a region wide hindcast at selected grid points since 1986. It should be noted that significant modifications to the model were made until 1993.

2.2.2 UK waters wave models

The UK waters wave model covers the north-west European continental shelf from 12° W, between 48° N and 63° N at a resolution of 1/9° longitude by 1/6° latitude (approximately 12 km). The UK waters model has a much better resolution of the coastline than the European wave model, and includes the effect of time-varying currents on the waves, using currents forecast by the operational storm-surge model. The model was introduced into the operational suite in March 2000 and runs four times daily from 00, 06, 12 and 18 UTC, taking hourly surface winds from mesoscale NWP to give a 48-hour forecast.

Waves in the tidal waters around the UK can be a combination of locally generated wind waves and remotely generated swell: both can be modified by tidal or storm-surge currents, which affect both wave height and wave period. Full wave energy spectra are routinely used in the wave model calculations but output is summarised as integrated parameters (H_s, T_z, θ) at each grid point. The total sea, wind sea, and swell sea are all calculated for each time step record.

The coastline is represented simply: by the land ocean boundary of the model grid. This physical limitation, together with the coarse grid bathymetry, provides for only coarse resolution of nearshore wave transformations. The nearest grid points to the land are generally too far away from the shoreline to be used directly in coastal process simulations. The grid resolution limits representation of parts of the south coast of England. For example, the Solent, which is a fetch limited basin that is only a few Km wide (Figure 2) and bounded to the south by the Isle of Wight, is not represented within the model at all. The sites used in the comparison are at the landward limits of the model grids.

Complete records of integrated parameters of the UK waters wave model have been archived for the period since 2000. Spectral files, which are not routinely archived by the UKMO, have recently been added to the regional archive data sets. The nearest grid locations to the wave buoys have been used as boundary conditions for input to finer resolution wave transformation models, to transform data to the buoy sites. The buoy and hindcast grid data are not generally suitably close that they can be termed truly co-located in this sense and direct comparison is limited to four of the sites on this basis.

Previous comparisons have been made between the model and buoy data on a worldwide basis, but these have been restricted to deep-water sites mainly on the continental shelf (Bidlot *et al*, 1999, 2002).

2.3 HR Wallingford HINDWAVE model

The resolution of the UK waters model is too coarse to resolve wave climate within the complex nearshore Solent basin (Figure 2) and swell conditions are unable to enter the partially enclosed area. A conventional wind wave hindcasting model, HINDWAVE, (Hawkes, 1987) is used to derive a synthetic wave climate in this area.

This model is driven by local winds derived from long-term deployments of anemometers in the wave generating area, provided in conjunction with the field instrumentation programme. The JONSWAP formulation, using spreading functions as suggested by Seymour (1977), is used to calculate wave climate within an enclosed area of irregular shape. The model has been configured to provide data for 6 points within the fetch limited basin, to an area that is unaffected by swell waves. An non-directional pressure recorder is co-located at one of the hindcast points (Figure 2).

The hindcast time series generated for this location dates back to 1991. The data at this site is used for the purpose of validation of the fetch limited wind-wave hindcast and particularly, to examine the validity of the JONSWAP formulation used within the model for high wind speed situations.

2.4 Wave transformation model

The hindcast wave data provides offshore boundary conditions to a ray tracing wave transformation model; this has been used to determine transfer function coefficients for the linear transformation processes, to each of the sites in the wave buoy network. An extensive network of transformation sites has been established at shallow water sites around the coast. The nearshore grid resolution is typically 50-100m. The model grids are refined as new nearshore bathymetric surveys are completed, and using data from the UK Hydrographic Office (UKHO) digital archive.

Time series are updated regularly, to provide a growing nearshore wave climate archive. Design conditions defined by extreme events with a given probability of exceedence are determined and updated, by fitting data to a 2-parameter Weibull distribution. Similarly, the data are used to provide event-by-event analysis of severe storms, in context with the beach monitoring programme.

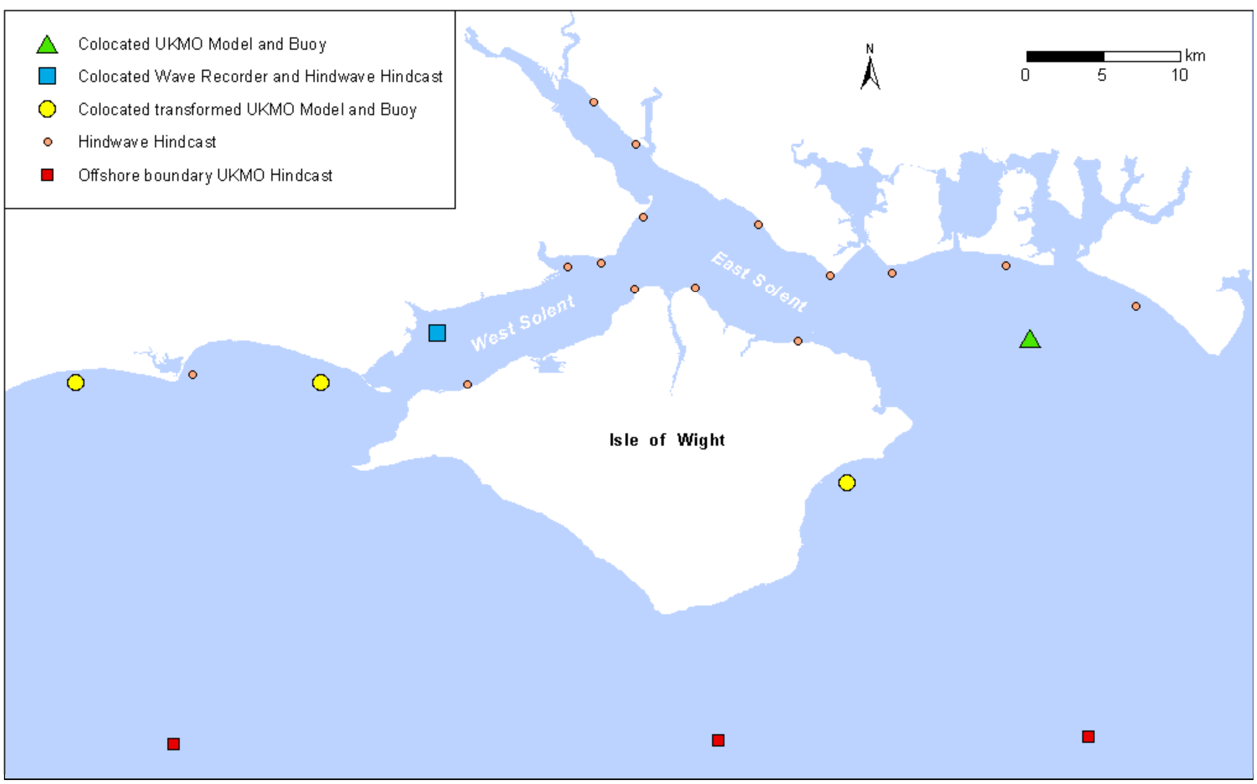


Figure 2. Location of wave recorder and modelled wave data points in and around the Solent

3 DATA COMPARISON

3.1 Validation of wave transformation and prediction models

Coastal buoy data are used routinely for validation of the UKMO models but are not used for data assimilation, because they would not contribute to further propagation of the waves, being at the landward model boundary (Bidlot *et al* 1999). Validation is still considered to be an important part of the shoreline management process and an extensive network of wave prediction points has been established in parallel with the wave measurement network, including for all wave measurement sites (Figure 1). The measured wave data is routinely compared with modelled wave data for model validation. Synoptic data sets are of variable lengths at the various sites. Records are available for all sites since July 2003, although some sites can provide much longer records (Table 1). Examples of the analysis are presented for a range of comparisons. Although the wave transformation and hindcasting models have been calibrated previously on a generic basis, with the aid of deep-water wave measurements, few long-term records of wave measurement are available in shallow water to provide local validation.

3.2 Potential problems with data comparison

The comparisons between buoy- and modeled-data are constrained by a number of differences in representation and calculation methods. Firstly, the UK Waters model is intended to provide a representative sea state for spatial coverage of each 12km grid square, whilst the buoy data is confined to single point measurements that may not be representative of a wide area. On this basis, the proximity of buoy and model sites and the local complexity of bathymetry and tidal currents needs to be considered carefully prior to making direct comparisons of hindcast data with the buoy data.

Local bathymetric variability becomes increasingly significant in shallow water, due to the impacts of local shallow water transformations, which can vary significantly across a 12km grid square. Whilst the UK Waters model includes some basic shallow water physics, the grid resolution is unable to resolve shallow water transformations adequately across a rapidly varying bathymetry. Grid points are not always suitably close to be considered truly co-located with buoy sites, under such shallow water conditions.

Where possible, buoy sites have been located close to model grid points; but restrictions such as shipping channels, local tidal currents and bed conditions have further limited the location of the buoy sites relative to the UK waters model grid points. Several of the buoy sites are suitably close to UK waters grid model locations (sites C, E, F, G Figure 1) that they can be considered co-located, in context with the buoy data.

At locations where the buoys are considered too distant from the hindcast grid points, or where the local bathymetry is complex, direct comparison is not sensible. Additional wave transformation modelling is needed to take account of local shallow water transformations between the hindcast grid point and the buoy. Non-linear transformation processes, such as bed friction, have not been included in the transformation model used. Similarly, the quality and density of the transformation model grid varies across the region, according to density of available bathymetric data.

Direct comparison between the two sources of time series data is difficult, because of the differing time bases of the measured and modeled data sets. Time averaging of the model output provides data at hourly or 3-hourly intervals, whilst buoy data is updated every 30 minutes. The model data is considered to be representative of the sample interval, whilst buoy data is indicative of 20-minute samples. Buoy data sets have been re-sampled to the same time base as the model for direct comparison, but some comparisons have also been made with unfiltered data to examine whether there is significant evidence of cropping of the peak conditions as a result of the sample interval, which is clearly below the Nyquist frequency. It is suggested that the hourly data gives a far closer representation of the wave climate than the 3-hourly data.

Previous approaches to validation of hindcasting models, using buoy data, have presented combined data sets for a number of sites (Bidlot *et al* 2002). It is considered to be more appropriate to examine each site separately in shallow water conditions, as shallow water transformations may have a significant local effect.

Analysis of spectral records from the buoys on the south coast of England indicates that the wave climate is frequently bimodal, with clearly defined swell and wind wave components (Figure 3). Under these circumstances the integrated parameter output produced by the hindcast model may be misleading and full spectral output can be valuable. Although the integrated parameters are usually the only wave parameters used in conventional coastal engineering empirical design formulae, the spectral shape may be of some significance to engineering design. The wave climate is often further complicated by differing directional sources (Figure 4), although any swell component invariably originates from the southwest. The swell component is usually more accentuated in the western Channel.

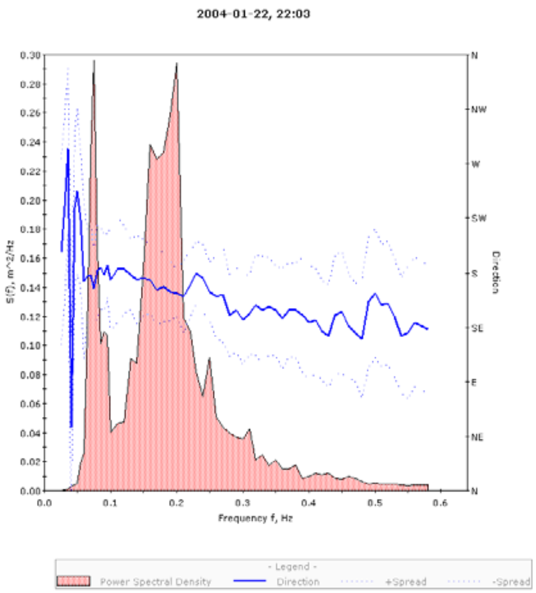


Figure 3 Spectral output from Boscombe Buoy showing bimodal sea

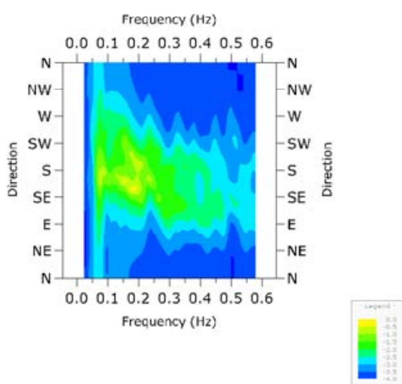


Figure 4 2-d spectrum showing bimodal directional spectrum in the eastern Channel.

The method of calculation of the wave parameters is considered to be a potential weakness in the analysis. T_p is clearly defined in both model and measured data, by the frequency at which spectral energy is highest. T_z is defined by zero up-crossings in both the UK Waters model and at the buoys. H_s is calculated by moments from the spectrum, in both instances, and direction is defined at the frequency of the spectral peak. Data should therefore be comparable for all variables. There are frequency resolution differences in both model and measured data and these are reflected by the spread of data within certain frequency bands for the UK Waters model.

3.3 Comparison of wave heights at co-located wave recorder and HINDWAVE hindcast model

Whilst most of the comparisons presented relate to the UK waters model, HINDWAVE (HR Wallingford, 1979) is used to generate wave climate data for sites within the Solent (Figure 2). These sites are fetch limited, within an area that has considerably smaller overall dimensions than the UK Waters grid size. Results from the HINDWAVE model are compared with a (pressure) wave-recorder off Lymington (Site C Figure 2).

Recent observations (Hawkes, perscomm.) have suggested that the standard JONSWAP formulation used within the model may under-predict wave heights at short-fetch-limited sites (<2Km), under extreme wind speeds. To date there appears to be no clear evidence to corroborate this, although conditions measured have not been particularly severe during the monitoring period. The scatter plot suggests a good general fit of the linear regression to the theoretical line. It should be noted however that there does appear to be some under prediction of wave height for the more extreme events, although the event frequency is not sufficiently high to enable a sound statistical comparison. Continued observations are planned at this site.

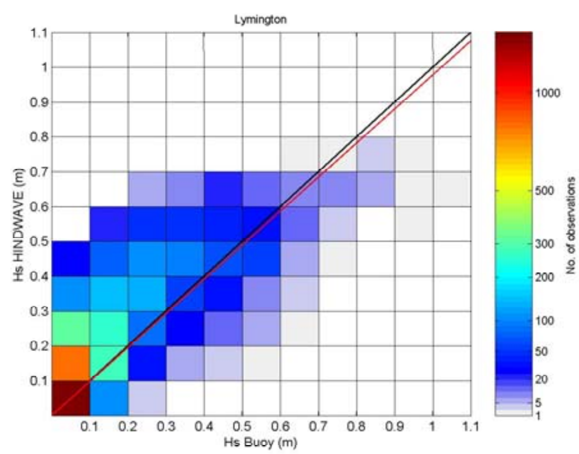


Figure 5 Comparison of the HINDWAVE model with measured wave heights at the Lymington (pressure) recorder site.

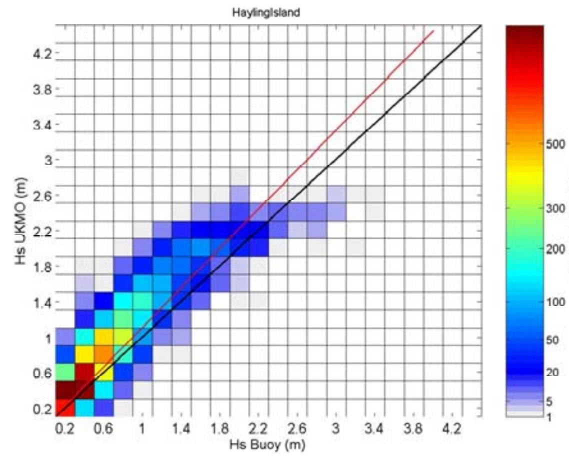
Comparison of period data presents somewhat less certain results. The model output has produced a sea steepness based upon a fully developed fetch limited sea, using the JONSWAP formulation with $\gamma=3.3$. This essentially provides for a limited range of wave periods in formulation, which is not the case in reality. Wave period measurements are not well represented over the high frequency range, in combination with low wave heights, and results should be viewed with caution.

3.4 Comparisons of wave height between co-located wave buoys and direct hindcasts from the UK waters model.

Results are shown for the sites that were considered to meet co-location criteria, when taking account of: bathymetry, water depth and distance from the buoy site. Wave recorders at Rustington, Hayling Island and Pevensey (sites E,F,G, Figure 1) all meet the relevant criteria for comparison with direct hindcasts from the UK Waters model, at the land-most grid point. Scatter intensity plots are shown for comparison of wave height (H_s) in Figures 6a-c. Combined data recovery rates for these sites are Hayling (96%), Rustington (89%) and Pevensey (91%).

Examination of the scatter intensity distribution plots of H_s (Figure 6) emphasizes the fact that the UK waters model typically has a positive bias and generally over-predicts the actual wave heights by about 10-20% at the Hayling and Pevensey buoy sites, for Hs<2m (Figure 6a,c). This is consistent with earlier observations determined for deep-water validation sites on the continental shelf (Bidlot *et al*, 1999). A better relationship is evident at the Rustington site (Figure 6b) where the data is correlated very closely with the theoretical distribution. This difference may be attributed to the more open location of the Rustington site, as opposed to Hayling and Pevensey where the geometry of coastal boundary conditions, may impact on results. Although the spread of data is wide, this is generally of limited concern in operational terms. Since water depths are only 10-12m at the buoy sites, it is difficult to determine whether any differences are reflective of the hindcasting model or of the inbuilt shallow water physics, which might be insufficiently aggressive when applied across a simplified bathymetry.

The distribution fits less well at the upper end of the measured range and the model appears to have a negative bias, under-predicting events with a measured H_s>3m (2.5m at Hayling). This is consistent at all sites where the direct hindcast was deemed to be valid, and is particularly notable at the Rustington buoy site, where predicted extremes are typically 10-20% lower than measured, typically for events with Hs >2.5m. A noticeable departure from the linear best fit trend is evident through the full data set, on each of the scatter intensity plots, for events with H_s>2.5m (Figures 6a-c).



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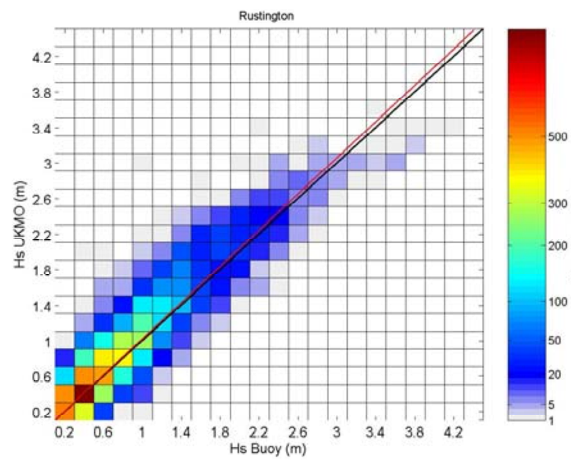

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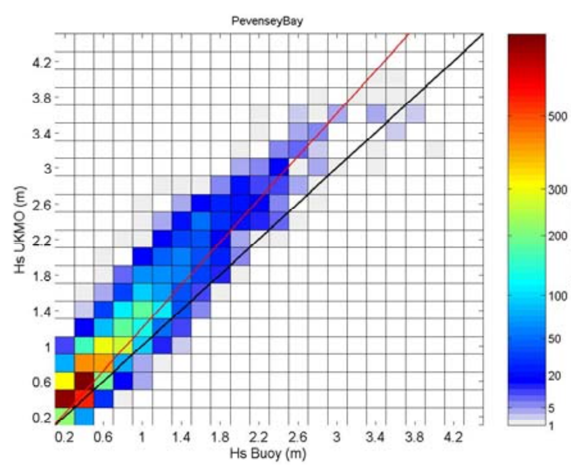


(6c)

Figure 6. Comparison of buoy hourly average significant wave heights with UK Waters hindcast data at (a) Hayling (b) Rustington and (c) Pevensey buoys site for one-year duration.

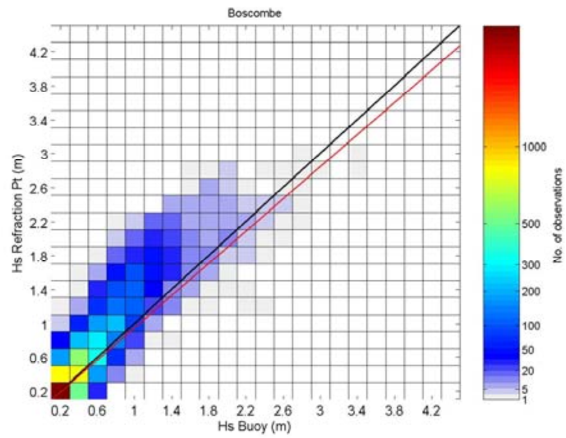
Although the instinctive reaction may be to attribute the variance between the modeled and measured wave heights to the wave model physics or algorithms, it is possible that such apparent model limitations may be due to an underestimation of the wind speeds from the NWP used to drive the model, for the more extreme events, as highlighted previously (Bidlot *et al* 2002). This is possibly due to the coarse representation of the land ocean boundary layer in the NWP models, resulting in a shore parallel ribbon of lower than actual wind speeds and a resultant limitation on growth arising from local wave generation. The English Channel presents a particular modelling problem for the shore parallel strip, at a distance of about 10-12km from the coast, with possible under-representation of a funneling effect of shore parallel winds through the Channel.

3.5 Comparison of measured wave height data with co-located hindcast data transformed to the wave buoy site

Direct comparison of the hindcast data with buoy data is inappropriate for some of the buoy sites, as the nearest model grid point is both distant from the site and is in significantly deeper water. In order to examine these sites, a suitable UK waters grid point has been used to provide offshore boundary conditions. Further transformations have been applied to the modeled data, using fine model grids (50-100m) and well-tested wave transformation models. This also provides an implicit test of the shallow water physics in the UK waters model. Waves have been transformed from deep-water hindcast grid points (typically 30m) to the relevant buoy site. Transfer function coefficients have been established for the linear processes at all sites, to transform the hindcast data to the buoy locations. Given the relatively shallow water, these have been determined using full tidal control, derived from a combination of measured and predicted tides. Combined data recovery for the sites shown are: Boscombe (91%), Pevensey Bay (91%) and Folkestone (72%).

The records indicate a generally good agreement, although the modeled data tends to under-predict wave heights at Folkestone and Boscombe. As the model includes transformation of the data to the wave buoy site, there can be no certainty that the errors arise in the transformation modelling, as opposed to the hindcast model.

The Milford wave buoy site (Figure 8) presents an opportunity to examine a much longer time period of wave data (9 years), and the possibility of a higher frequency of occurrence of the more extreme events, within the band of wave heights that appears to be under-represented by the UK Waters model at the sites with just a single year of data.



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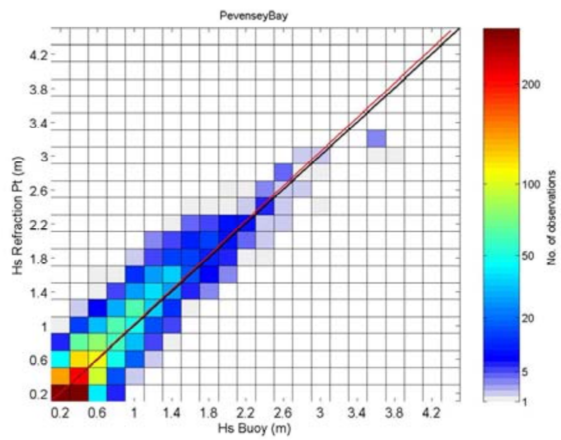

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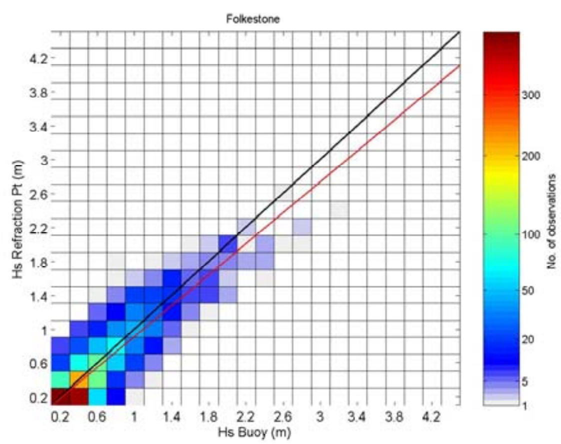


(7c)

Figure 7. Comparison of hourly average significant wave heights with UK Waters hindcast data transformed to (a) Boscombe, (b) Pevensey Bay and, (c) Folkestone wave buoy site for one-year duration

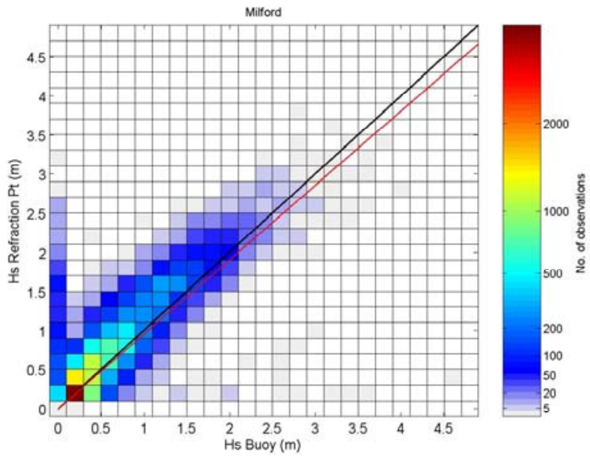


Figure 8. Comparison of modelled and measured distribution of H_s at Milford-on-Sea between 1995-2004.

These results contrast with the direct hindcast, which indicates a slight positive bias; this may be reflective of the increased intensity of the shallow water transformations represented by the combined hindcast and transformation approach. The very good fit of the data at Pevensey (Figure 7b) contrasts with the direct hindcast to the same site (Figure 6c) and suggests that the fine grid resolution refraction model performs better than the shallow water processes within the UK waters model at this site.

The relationship highlighted in the shorter time records is confirmed, with a tendency for the severe storm events with a low probability of occurrence to be under-predicted by the model. The buoy data partially pre-dates the quality-controlled data sets from the more recent buoy deployments and hence shows more spurious data. The large data set (32,000 pairs of 3-hourly points) shows encouraging overall trends and confidence in both the offshore UK waters hindcast and the wave refraction model, for most conditions.

3.6 Examination of wave period

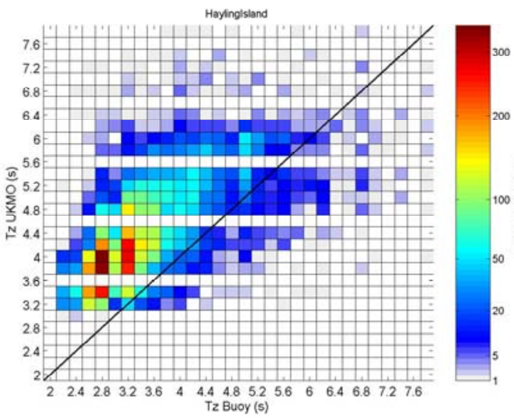
Accurate prediction of wave period is important in a coastal engineering context. In UK waters the range of wave periods between about 5-10 seconds are of most significance (related to storm waves), although long period swell can also be significant when wave heights are also high. Prediction of wave run-up and overtopping on beaches and coastal structures both require well-defined wave period data for application in empirical design methods.

The wave period output from the UK waters model and the wave buoys are both defined by zero up-crossings and are directly comparable. Scatter plots of wave period are examined and typical distributions shown for direct hindcast conditions (Figure 9a-c). All sites show similar characteristics. Similarly, the data sets transformed from offshore grid points to the buoy sites show very similar characteristics (Figure 10a-c). The UK waters model generally over-predicts wave period for T_z<5s. Analysis of a truncated data set for T_z<5s suggests that the UK Waters model typically over-predicts wave period by at least 20-30% within this range. Data is extremely widely scattered about the theoretical fit. The modeled data behaves more satisfactorily for wave periods 7>T_z>5 but data is very widely scattered about the theoretical line. In all cases the data is more widely scattered than is desirable, particularly for periods where T_z>5s i.e. those conditions that might be used to define design events. The wide scatter of data for T_z>5s, does not present a clear relationship between buoy and model, and the frequency of events is not sufficiently high to provide a reliable statistical fit of the data. The frequency of occurrence of longer period waves (>5s) is much lower than for shorter period waves, as they are typically associated with storm conditions, but these are the events of most interest to the coastal engineer, in terms of potential for flooding and damage.

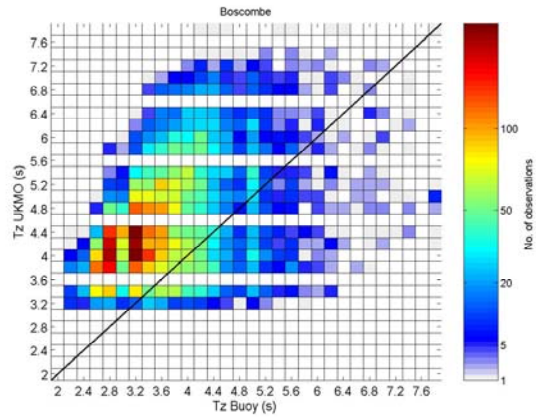
The wide scatter of results suggests that some improvements to the model would be useful, particularly in context with predicting wave overtopping. Representation of the frequency resolution within the model is coarse; this impacts on the ability of the model to represent growth of the wave period in a well-defined manner. For instance, the range of periods from 3.1-5.2 seconds is represented in the model by just 3 frequency bins and the lower limit of frequency resolution is 3.1s. The frequency resolution of the UK Waters model is represented by only 13 frequency components in total, and the method for calculating the peak period is simply to choose the component with maximum energy. For low frequencies, when the discretized frequency components are spread the most, the model peak period might be crudely estimated (Bidlot et al, 2002). On this basis, the model should not reasonably be expected to provide well-defined correlation with the buoy data, although this is desirable. Stratification of the modeled data is evident within the output (Figures 9,10); this is a characteristic of the model frequency resolution and a recognized limitation over this range. An expectation of precise replication of the buoy data is unreasonable therefore. This limitation is recognized by the UKMO modelers to be a likely cause of the scattered definition of wave period. More detailed representation of the frequency resolution within the model is likely to overcome these difficulties and this is recommended for further investigation and development.

Buoy measurements of the period at the peak of the one-dimensional wave spectrum (peak period) are harder to compare with model estimates because of the different methods used to determine them; these have been omitted from this investigation on this basis. A global inspection of similar scatter diagrams has already indicated the Met Office model tendency to overestimate the peak period (Bidlot *et al* 2002). Furthermore, it appears that low buoy values are overestimated but large peak periods are under-predicted; this is consistent with the T_z observations for this investigation.

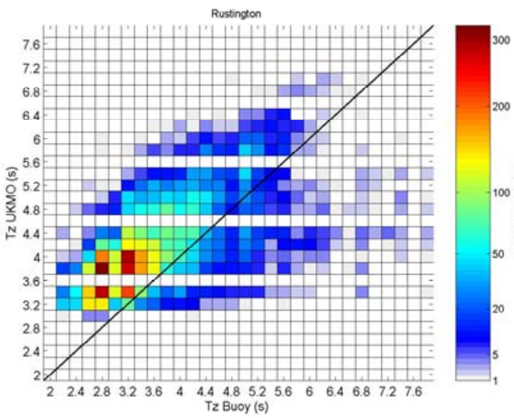
(9a)



(10a)



(9b)



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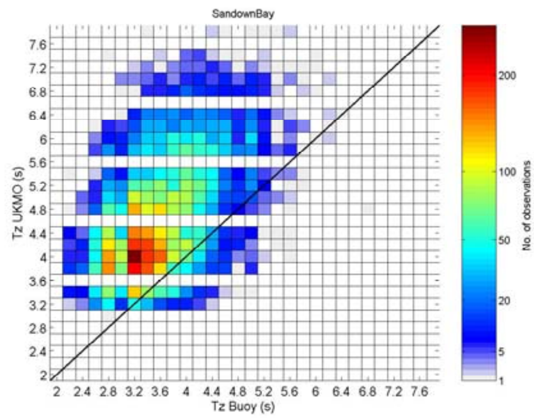
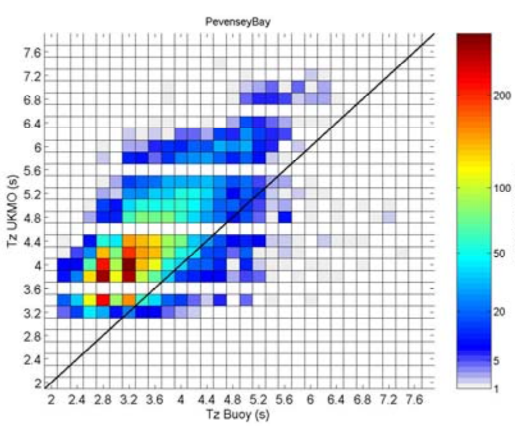


(9c)



(10c)

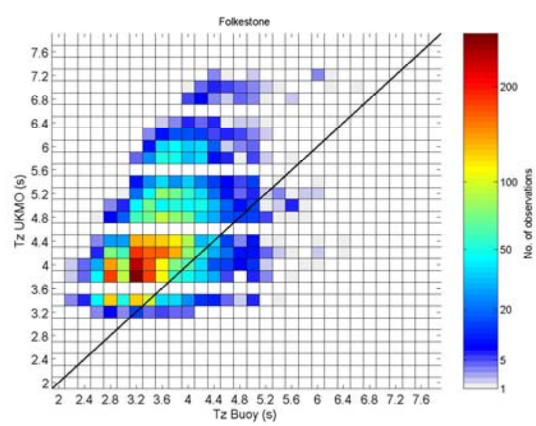


Figure 9 Comparison of hourly average wave periods (Tz) with UK Waters hindcast data at (a) Hayling, (b) Rustington and (c) Pevensey wave buoy sites for one-year duration

Figure 10 Comparison of 3-hourly average wave periods (Tz) with UK Waters hindcast data transformed to (a) Boscombe (b) Sandown and (c) Folkestone wave buoy sites for one-year duration

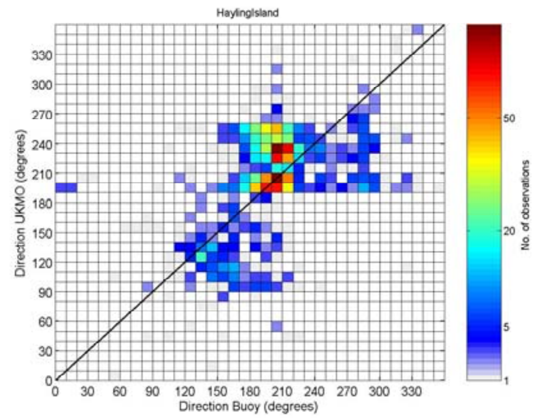
3.7 Comparison of wave direction

Measurement of wave direction at the buoy sites has presented some difficulties at the shallow water sites. The buoys are moored close to the (shallow water depth) limits of their operational range, but currents at each site are theoretically well within the acceptable range of response of the mooring system. The shallow water conditions are compounded by the impacts of tidal currents and their influence on wave direction. Since longshore sediment transport models are particularly sensitive to small changes of just a few degrees, the accuracy of data sets providing input wave conditions are critical. Ideally the direction resolution of the data needs to be reliable within about 5^{o} to achieve reasonable estimations of longshore transport rates; this is an extremely onerous requirement of the model, and which does not accord with the original model design, which has a directional resolution of ?^{O}. The implications of bi-directional wave climate are significant in sediment transport terms and the integrated parameters output from both buoys and models provides an average in this context. The spreading calculation at the buoy provides an indication of directional variability and this serves to identify that the engineer's requirements cannot be met with the output from either buoy or model. This is an issue of particular concern since the time series are regularly used as input to beach plan shape models, used to predict coastal evolution.

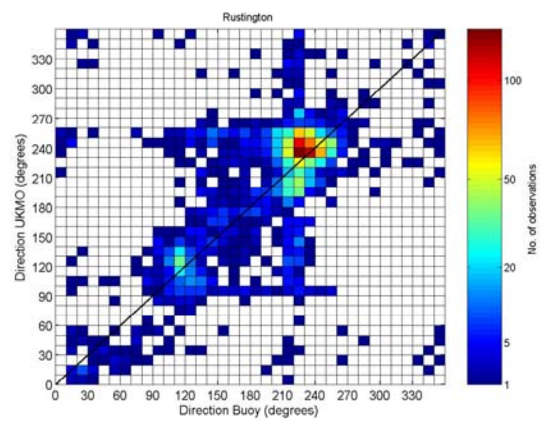
The comparison of directional data does not provide a clear picture and the widespread scatter of data is difficult to interpret, although it should be noted that the widely scattered data has a low frequency of occurrence. The representation of direction on the scatter plots is complicated by the circular definition of wave direction and consequently scattered data is to be expected, in the corners of the plots, in the sector between 340-020^{O}. Examination of the time series suggests that the model shows larger and more rapid swings in direction than the buoy suggests. The influence of tidal currents has not yet been examined in detail and these may play an important part in the output. The predominant wave direction (230- 240) is clearly defined, together with a secondary peak, for all of the sites. The correlation between measured and modeled data appears to be reasonable for events with a high frequency of occurrence.

The distributions for the Hayling and Rustington sites appear rather more orderly than at Pevensey where data is more widely scattered. Further examination is planned to evaluate the accuracy of buoy measurement procedures for direction; this will include co-location of alternative wave measurement equipment (ADCP) and GPS buoys together with the existing accelerometer based instrumentation. Currently the confidence in the data sets is low and there are concerns that either the buoys or the model could be problematic.

(11a)



(11b)



(11c)

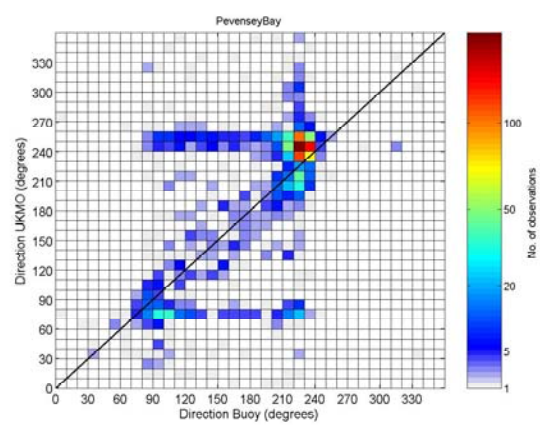


Figure 11. Comparison of directional buoy and UK Waters model data at (a) Hayling (b) Rustington and (c) Pevensey

3.8 Reproduction of storm events

The reliability of the modelling of shallow-water wave conditions is most crucial in storm events, particularly for predictive forecast modelling of overtopping, breaching of structures and beaches, and structure stability. The scatter plots of measured and modeled wave heights suggest that a more detailed examination of extreme conditions (H_s>3m) is required. Time series have been compared for a series of selected storm events.

Results are shown for the storm period peaking on January 8 2004 (Figure 12). Regional variability and progression of the event through the English Channel is observed on the time series plots, which are numbered sequentially from west to east (12a-d). The buoys consistently indicate higher storm peak values of H_s than the UK Waters model. A similar pattern was noted for most other major storm events, at all buoy sites, during the 12-month comparison period. The pattern of model over-prediction of wave heights, for conditions where H_s<2m, is also evident in the time series. These observations confirm the broad-scale comparisons identified in sections 3.3-3.5.

The direct hindcasts to Hayling (Figure 12b) and Rustington (Figure 12c) sites are supplemented by data transformed to the buoy site from a UK Waters grid point at an offshore boundary, using a fine resolution refraction model. The two sets of modeled data follow similar patterns, suggesting that the shallow water processes and the grid resolution provided in the UK waters model are reasonably representative of these sites.

The time series records also assist with testing the accuracy of phasing within the model. This does not appear to be an issue, with the peaks of events coinciding in both UK waters model and at the buoys.

Wave periods associated with the same events, (not shown) are typically 10% longer in the model than those measured at the buoy sites. The buoy wave-period time series shows a notable tidal signature that is not identified in the UK Waters model output.

In coastal engineering design terms, the difference between measured and modeled wave height data is significant, for extreme events. For instance, the stable rock-armour size is (roughly) proportional to the cube of the wave height. Small changes in extreme conditions may have significant stability implications therefore. The implications of over prediction of wave period may result in overly conservative design of flood-defences, or issue of unnecessary flood forecast warnings.

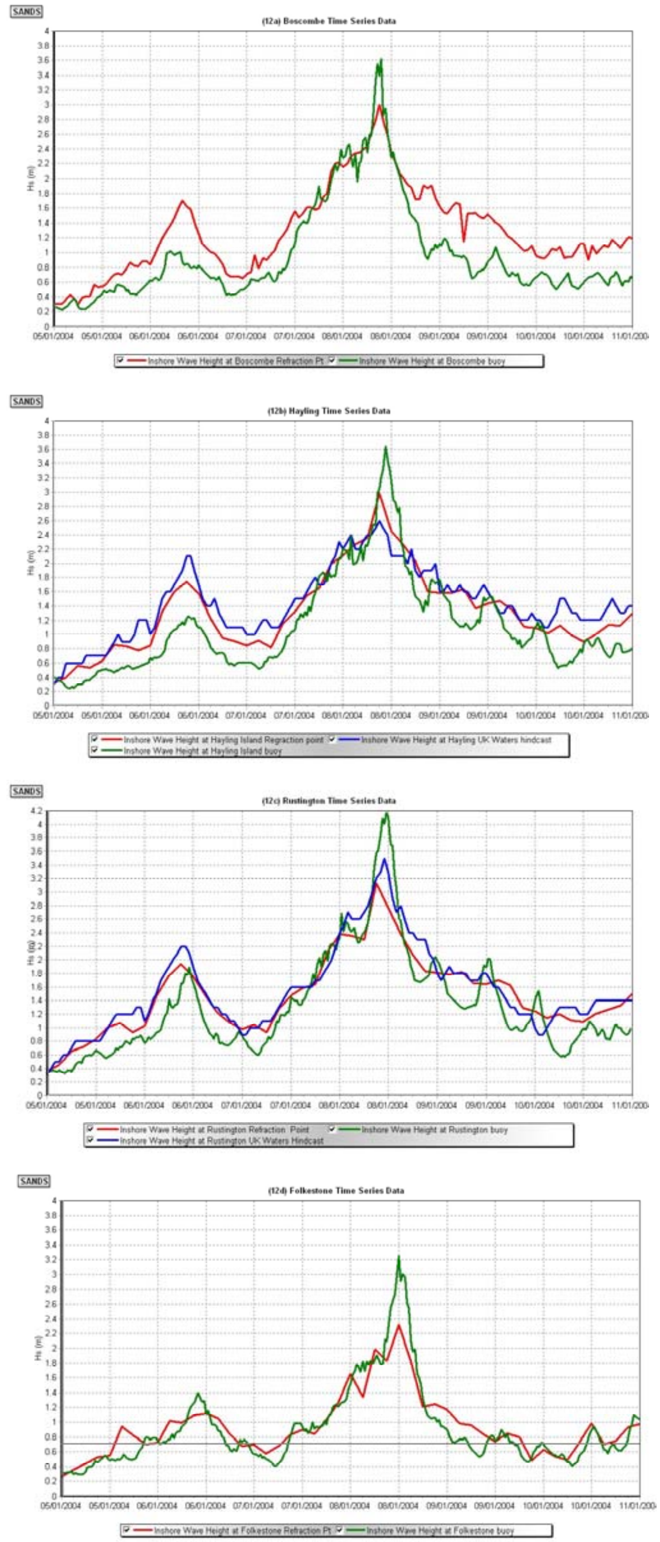


Figure 12. Modelled and measured wave height time series for storm event (8/01/2004) at English Channel wave buoy sites.

3.9 Variability of wave steepness

The shallow water wave steepness (s) is used widely in empirical design methods, for evaluation of the impact of wave-structure interactions. Variability of wave steepness has significant implications for the performance of structures, with reference to both overtopping and stability, and for cross-shore sediment transport on beaches. Examination of wave height and period combinations (Figure 13) provides an opportunity to determine the measured and modeled wave steepness combinations.

The scatter plots highlight the fact that extreme wave height events are typically under-predicted by the UK waters model. Maximum wave heights are typically about 10-15% higher at the buoys. The Pevensey site suggests rather better correlation in this respect.

The leading diagonal edge of the scatter plots delimits the conditions represented by the limiting steepness, as defined by the wave energy spectrum and defines those events that are typically associated with stormy (steep) wave conditions, for the higher values of H_s, i.e. the upper right region of each of the graphs. This is the area of most interest from a design and management perspective. The UK waters model uses a JONSAP formulation with a γ value of 1?. The measured buoy data is more representative of a TMA shallow water spectrum, generally showing much steeper combinations of wave conditions.

Analysis of the pairs of scatter plots shows a clear difference in wave height and period association, with the UK Waters model generally showing significantly longer wave periods for comparable wave heights i.e. the wave steepness is lower in the UK Waters model than at the buoys. The frequency resolution of both the buoys and the UK Waters model is highlighted, with the UK Waters high frequency cut off at 3.2s and the buoy at 2.2s. Model frequency resolution issues are also noted with stratification of wave periods evident within the plots. The UK waters model suggests that the most frequently occurring periods are at about 3.8s whilst the comparable buoy measurements indicate a period of 2.8s. The wave height intensity correlation shows very good agreement between the model and buoy records.

An examination of wave periods associated with defined wave height conditions typically indicates that periods are at least 10% longer in the UK Waters model, for the extreme events. For example, the steepest wave height-period combination for H_s=3.4m at Rustington is represented by a period of 5.5 s (buoy) and 6.8s (UK Waters). A common pattern is shown for all sites.

Overall the buoy data distributions indicate a marked difference in association between modeled wave height and period combinations. The difference in wave steepness is notable for the more extreme events (Hs>2.5m). This difference is highly significant in terms of designing, or predicting the behaviour of beaches and structures under design (extreme) events, which are likely to occur with the steepest combinations of wave height and period.

4. DISCUSSION

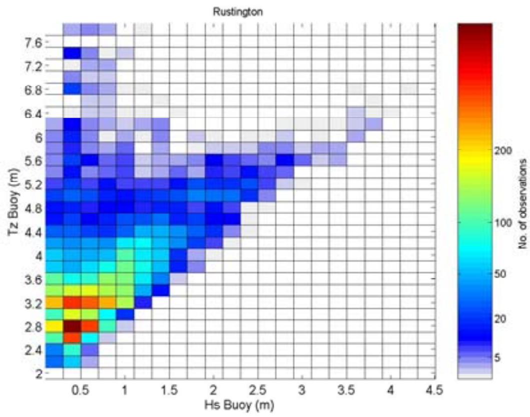
The buoy network provides useful validation for the UK Waters model, and for the wave transformation models used within the southeast strategic regional coastal monitoring programme.

The implications of model and measured variability can be assessed in context with coastal engineering and flood defence, by examination of each of the integrated parameter values. Specific improvements to the model are suggested to overcome these difficulties, and these can be considered in terms of the overall prioritisation of future UKMO model developments.

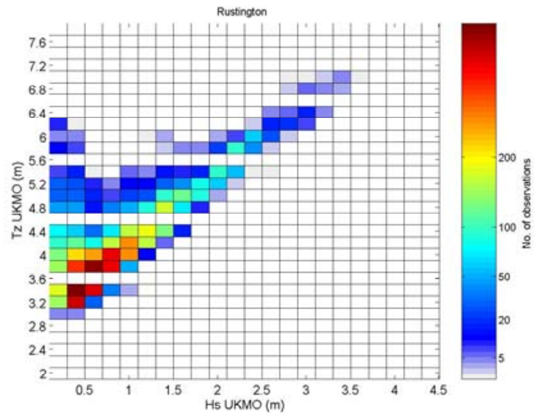
Significant wave height is generally well represented within the model although extreme events (H_s>3m) are represented less well. The UK Waters model appears to under-predict extreme events at shallow water sites; this may have significant implications for stability calculations on rock-armoured structures. The implication is that users of modeled data may under-design the size of rock-armour, or the structure slope angle. Refinement of the model to deal with this range of conditions would be advantageous, although this may also require improvement of the resolution of input winds derived from the NWP models.

Representation of wave period appears to be more of a problem within the UK waters model, at least within the central and eastern section of the English Channel. The model frequently over estimates wave-period. This has potentially serious implications for estimation of wave run-up on beaches and structures, and particularly for the volume of water discharged in overtopping events. Over estimation of wave period is likely to produce overly conservative, and more costly, engineering designs for flood defence structures such as sea walls. Improvement of the frequency resolution of the wave period within the UK Waters model would be beneficial and this may help to reduce the current wide scatter of results.

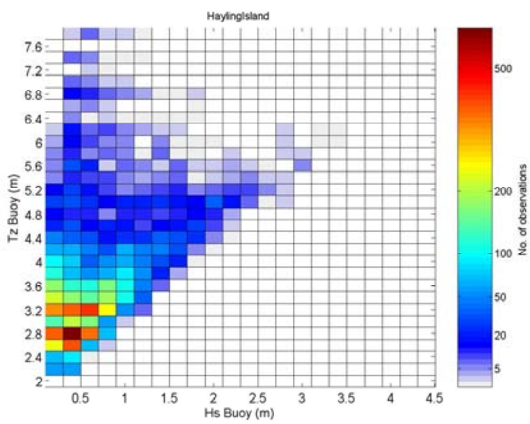
(13a1)



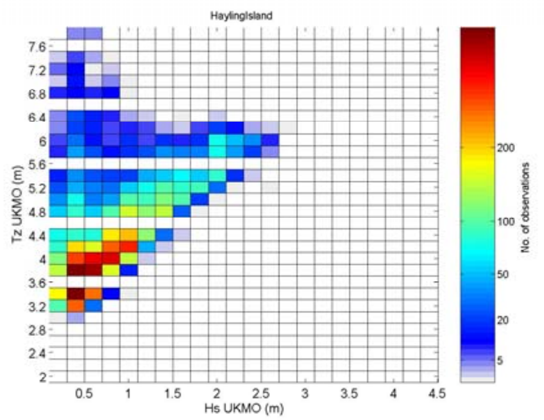
(13a2)



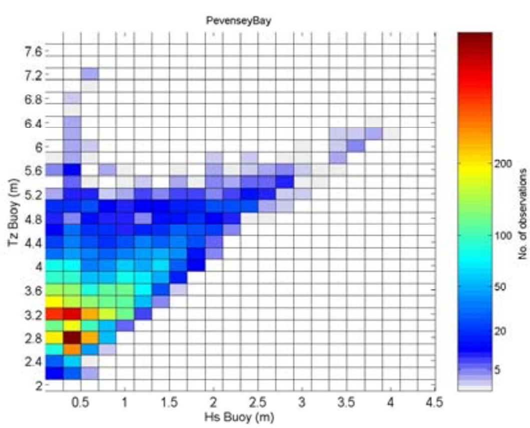
(13b1)



(13b2)



(13c1)



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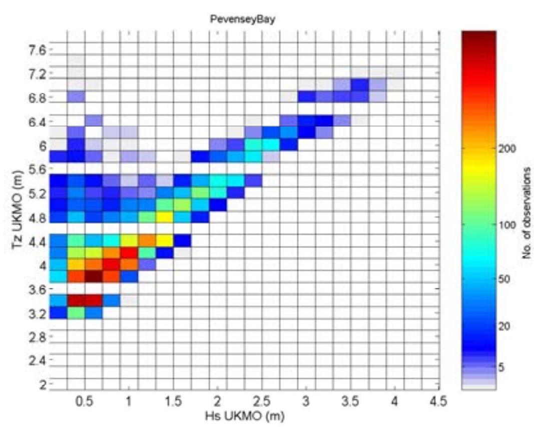

Figure 13 Scatter intensity plots of wave height and period distributions for wave buoys and the UK waters model

At this stage no recommendations are presented to modify representation of wave direction in the model, but further examination of the buoy data is required. The current resolution of direction within the UK Waters model and the wave buoys is inadequate to provide reliable input to longshore sediment transport models, although the actual requirements (<5^{O}) may be somewhat unrealistic to achieve. More detailed examinations of the buoy wave direction data are required.

The combined wave period and wave height variability results in prediction of waves with differing steepness, which is of some concern in engineering terms. Independent improvement of the wave height and period parameters, outlined above, would resolve this problem.

The benefits of the higher sampling rate of buoy data (30min) are highlighted, by comparison with the model (1hr or 3 hr). It is suggested that the UK waters model integrated parameter archives, developed for long-term wave climate studies, should routinely comprise hourly records, or better if available; this approach is more likely to identify the relevant storm peaks.

The main areas of concern relate to extreme conditions, which necessarily relate to data sets which are not highly populated and hence of limited statistical significance. Focus needs to be placed on validation of storm events above a defined inshore wave height threshold (Hs>2.5m).

Real time flood forecasting applications, based on synthetic data forecasts, are currently likely to suggest that areas are at flood risk more often than is actually the case (within the southeast of England); this is likely to reduce the confidence of the public in these predictions. Additional caution needs to be considered when using the integrated parameters as opposed to the full energy spectrum, when there is a significant long period component in a bimodal spectrum.

Although improved quality and accuracy of data is desirable from a scientific point of view, the required data quality for operational forecasting and hindcasting models depends upon the eventual application of the data.

5. FUTURE DEVELOPMENTS

A joint initiative between the UK Metoffice, HR Wallingford and the Channel Coastal Observatory is providing a new real time wave nearshore forecasting service based upon the buoys and models discussed in this paper, but used in forecasting mode. Currently trials are being conducted using the Sandown Bay wave buoy for validation.

6. ACKNOWLEDGEMENTS

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