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Marine forecasts for the safe construction and maintenance of coastal structures

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MARINE FORECASTS FOR THE SAFE CONSTRUCTION AND MAINTENANCE OF COASTAL STRUCTURES

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Introduction

The BBC Shipping Forecast is a highly respected and widely used service, but optimising marine engineering operations in shallow coastal waters (see for example Figure 1) requires much more detail about winds and sea conditions. Site specific, accurate and reliable real-time predictions are needed to manage construction and maintenance schedules during marginal sea conditions in amongst shallow banks and strong currents. HR Wallingford and the UK Met Office have combined their respective skills and modelling capabilities to develop a forecasting system that has been used by LNG terminals, Network Rail and the Royal Navy.

This system has been now been applied to the UK renewable energy industry; in particular for the construction of the Lynn and Inner Dowsing Offshore Wind Farms off the Lincolnshire coast and at Gunfleet Sands Offshore Wind Farm in the Outer Thames Estuary (as illustrated in Figure 2) where one of the key constraints for construction are the met ocean conditions.

Each of these wind farms is located in areas where waves are influenced by shallow banks and currents, causing e.g. wave refraction, shoaling and breaking, resulting in spatially diverse wave conditions.

Forecasts of the marine conditions are required to inform planning decisions that maximize cost efficiency and minimize health and safety risks. Site specific operational forecasts of the prevailing winds, waves and water levels are provided by HR Wallingford and the Met Office. Users of the forecasts map the respective operational constraints to the forecast data provided to determine suitable 'Weather Windows' in which to carry out operations.

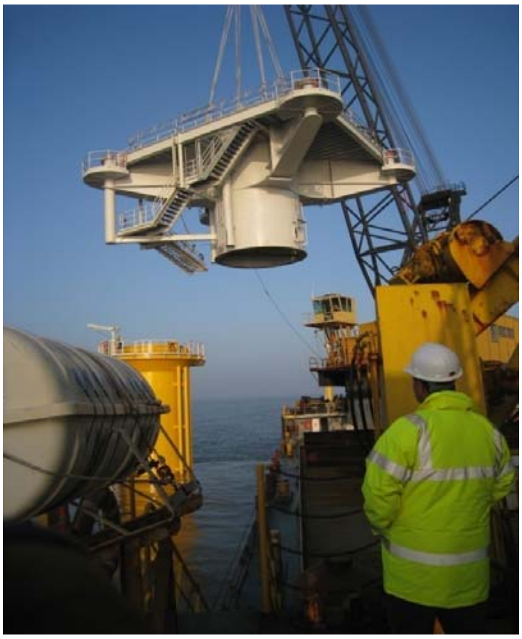


Figure 1 Weather sensitive heavy lift operations in the Outer Thames Estuary

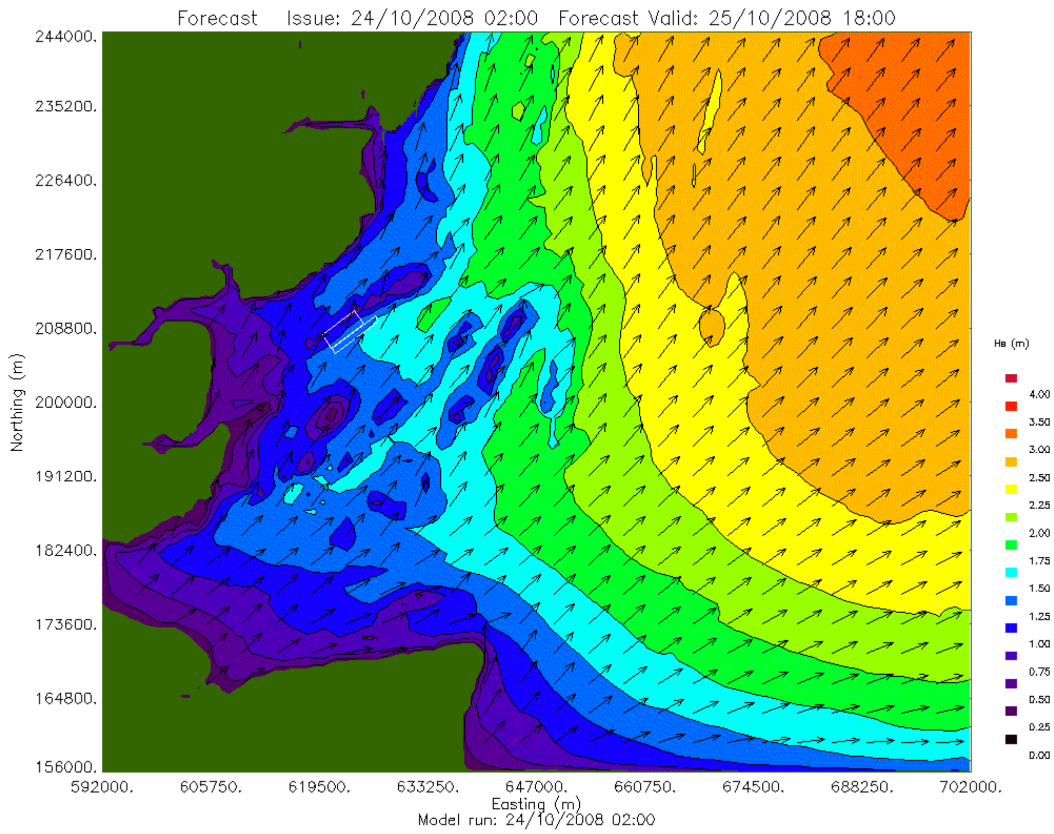


Figure 2 Operational wave forecast conditions in the Outer Thames Estuary

For the Gunfleet Sands Offshore Wind Farm, the first of the UK Round Two offshore wind farms to be constructed, the marine forecasts are integrated within a spatial planning tool. This tool combines information on the meteorological forecasts, the position and status of the pile foundations, cables, and turbines, and vessel data in a live web environment to support the wide range of marine operations, equipment and personnel. The forecasts are available to all members of the construction team allowing decisions to be made and monitored using a consistent data source. A summary of the marine forecasts as tables and graphical output (see Figure 3) are also disseminated by email to members of the construction team.

This paper describes the Met Office and HR Wallingford wave forecast systems, illustrated with details of the wave forecast models used for the Gunfleet Sand Offshore Wind Farm development, although the methodology and information provided is equally applicable to many weather sensitive construction and maintenance of civil engineering marine operations. These systems have also been extended to provide response e.g. beach run-up, overtopping and surf zone forecasts where required. This paper also includes an outline of the spatial planning tool used for the Gunfleet Sands development, together with validation of the wave forecasts for a site within the Outer Thames Estuary.

Forecast model and methodology

Met Office Wave Modelling Forecast Systems

The Met Office runs an operational suite of Numerical Weather Prediction (NWP) atmospheric and wave models. The models provide predictions of wind and sea-state up to five days ahead at regular times daily on a year round basis.

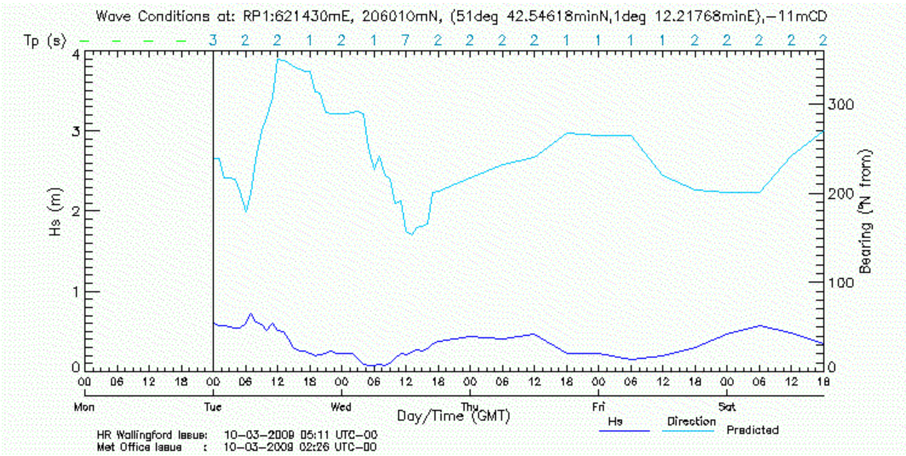


Figure 3 Example forecast wave conditions graph

The atmospheric models describe a three-dimensional grid field of atmospheric variables (wind, temperature, pressure, moisture) both as an estimate of the atmospheric conditions in the present (the 'analysis') and transported forward in time (the 'forecast'). Since 1991 a Unified Model has been in use at the Met Office for both low-resolution climate modelling and high-resolution operational NWP. This system is regularly upgraded to take advantage of improvements in both NWP techniques and climate research.

Data assimilation produces the analysis by combining up to the minute global observation data with the model's background field (a forecast from an earlier model run) whilst taking account of the likely statistical errors in both. This is a key stage in the NWP process since subtle changes in these initial conditions can alter the subsequent short period forecast significantly. The Met Office model uses a variational assimilation method described by Lorenc et al. (2000). The predictive part of the Unified Model uses a non-hydrostatic, fully compressible deep atmosphere formulation based on a terrain-following, height-based vertical coordinate (Davies et al., 2005).

The forcing parameters provided to the wave models comprise hourly 'snapshots' of wind speed and direction at a standard 10m height above sea level. The winds drive a spectral wave model, which in the case of the present operational system at the Met Office is a version of the third-generation spectral model WaveWatch III (WW3), which has been developed and released by the wave team at the US National Center for Environmental Prediction (NCEP).

At a regional scale, wave models must describe four key processes, namely: growth of waves due to wind forcing; dissipation of wave energy due to effects such as 'whitecapping' and bottom friction; cascading of energy to lower frequencies through nonlinear interactions; propagation of unforced 'swell' energy. In the present Met Office configurations of WW3 these processes are parameterized using:

- the Tolman and Chalikov (1996) source term scheme; which comprises Chalikov and Belevich (1993) and Chalikov (1995) schemes for wave growth along with the dissipation scheme of Tolman and Chalikov (1996)
- the Discrete Interaction Approximation (aka 4-wave interaction) scheme for nonlinear energy transfer (following Hasselmann et al. 1985)
- a Met Office second-order swell advection scheme – this was chosen to optimize model run time whilst ensuring that numerical errors in swell propagation (e.g. the so called 'garden sprinkler effect') are minimized.

Depth information for the model grid uses a representative average for each cell. This assumption may prove important in some near coastal grid cells where the average depth may mask bathymetric features affecting the local distribution of wave energy. A cut-off depth is set in the model scheme at 200m, since at depths greater than this value shallow water effects are negligible even for wave energy in the lowest frequency range.

Operationally the models are configured with a spectral resolution of 25 frequency bins and 24 directional bins, representing waves with a range of periods between 25 seconds and 3 seconds (deep-water wavelengths from 975 m to 15 m). Wave conditions worldwide are forecast using the Global Wave Model on a 5/9 degree latitude by 5/6 degree longitude grid (approximately 60km square grid at mid-latitudes), with fields output at 3-hourly resolution to a lead time of 5 days (T+120). This model is forced using the Met Office's Global domain NWP 10m wind field and run twice daily based on 0000 and 1200 UTC analysis times. The extent of ice cover at high latitudes is updated daily using a global sea-ice analysis based on the Met Office OSTIA scheme.

Boundary conditions from the Global Wave Model are used as input to a North Atlantic European Wave Model, which uses a rotated 1/9 degree latitude by 1/6 degree longitude grid (approximately 12km) covering a region from approximately 68°W to 30°E and 25°N to 65°N. Two configurations of the NAE wave model are run. The first configuration is forced by high resolution NAE NWP 10m winds and is run four times daily using analysis times 0000, 0600, 1200 and 1800 UTC and provides hourly forecasts out to T+36. The second configuration (Extended NAE Model) is run twice daily (0000 and 1200 UTC analyses) forced by Global NWP 10m winds in order to provide 3-hourly forecast data out to T+120.

Data are output from the model comprise:

- 2D wave spectra
- Overall significant wave height (calculated from the entire spectrum)
- Peak wave period
- Overall mean wave period
- Overall mean wave direction
- Wind-sea significant wave height
- Wind-sea peak wave period
- Wind-sea mean wave direction
- Primary Swell significant wave height
- Swell mean peak period
- Swell mean wave direction

which are variously retained in commercially available fast-access hindcast archives and research based forecast model archives. Due to data handling constraints two-dimensional (frequency-direction) spectral data are output at specific model points only and are not archived.

Forecast Intervention

The Met Office experience with issuing wave forecasts based on its 2nd Generation model has been that the human forecaster can make significant impact on forecast skill and data quality within the first 36-48 hours ahead. In particular, forecasters have been able to positively intervene with regard to the resultant significant wave height and characteristics of the swell component. WaveWatch III is a relatively recent introduction, and the impact of the forecaster on the most recent operational model forecasts is in the process of being assessed.

When choosing to intervene (or otherwise) on a model forecast, the bench forecaster at the Met Office relies on a set of basic tools and quality checks, including:

- Observations within the sea area of interest
- World Meteorological Organisation (WMO) approved nomograms
- Fetch calculations for the site of interest
- Experience of model performance in given situations.

Observations provide an excellent cross-check and method of intervention for resultant wave parameters, since such wave statistics are generally well correlated on the order of hours. As a result, corrections to a forecast based upon judicious application of observed data versus model data error can positively impact the final forecast up to approximately 12 hours ahead.

A further sense check on the wind forced significant wave height and period is available by assessing the forecast value against WMO nomograms, which allow the forecaster to derive wave height and period based on an understanding of wind speed and the duration for and fetch over which the wind blows. This approach to quality checking the wave model is of particular use in near coastal areas, where the regional model land-sea mask may not accurately reflect the true fetch.

For many services, and in specific regions of interest, it is good practice for forecasters to establish logs including known issues with model performance under specific circumstances. This provides a source of reference that aims to ensure the model forecasts are subject to particular scrutiny at times when their performance is most likely to be an issue, and enables a forecaster to review previous interventions. Ensuring that the forecaster understands characteristic behaviours of the model is particularly important for interventions relating to parameters such as the swell component, the performance of which will be highly dependent upon the diagnostic scheme used.

For the Gunfleet Sands Offshore Wind Farm intervened forecasts are provided at two locations providing forecasts of offshore wave conditions and nearshore wind conditions, respectively. These conditions are subsequently used in a local, higher resolution wave forecast model described below.

HR Wallingford downstream wave modelling forecast systems

For fetch or depth limited sites and areas with complex and relatively shallow bathymetric features not resolved using regional models e.g. as run by the Met Office, high resolution models are required to provide sufficiently detailed, reliable and accurate forecasts.

Due to the bathymetric profile of the Gunfleet Sands site, and the Outer Thames Estuary in general, the wave regime is spatially diverse. To provide accurate forecasts in the Outer Thames Estuary a SWAN spectral wave model (Booij 1996, Ris 1997) was set up to represent the processes of wave transformation from offshore and the generation of waves within the Estuary.

SWAN simulates the generation and propagation of random directional waves considering the following processes:

- Wave shoaling
- Wave refraction
- Energy dissipation due to depth-induced breaking, bottom friction and whitecapping
- Wave reflections from structures or rocky shorelines
- Nonlinear wave-wave interactions

Application of SWAN model for forecasting at Gunfleet Sands

The SWAN model was set up to cover an area of approximately 100km by 90km, extending offshore to the location of the Met Office model point. The SWAN model bathymetry included survey data provided by the Client. The extent of the model covers the shallower areas within the Outer Thames not accurately represented by the Met Office UK Waters wave model. Sensitivity tests indicated that a grid size of approximately 1km was optimal for model efficiency without significantly affecting accuracy.

Driving conditions used in the SWAN model include the Met Office forecaster intervened forecasts of offshore wave conditions and local wind conditions. Standard JONSWAP spectral shapes and $\cos^2(\theta)$ directional spreads were fitted to the offshore wave conditions. The local wind was applied uniformly over the whole SWAN model area.

The water levels for each time step were based on standard tide levels predicted at the near by location of Clacton-on-Sea. Each forecast time step was simulated in SWAN assuming steady state / stationary model conditions and the effects on waves due to currents and spatially varying water levels were ignored.

Due to the diverse wave regime over the Gunfleet Sands site model, forecast outputs were provided at five points across site.

These were used as input to a geospatial planning tool where the forecast outputs can be viewed either graphically or in tabular format. A summary was also provided by email combining textual and graphical output alerting users to forthcoming conditions.

SeaPlanner Geospatial planning tool

The geospatial planning tool Marine Manager was used at Gunfleet Sands Offshore Wind Farm. This is a planning, control and audit tool that was developed by SeaPlanner which displays geospatial and live feed data in a web environment and was designed to improve the safety and efficiency of marine operations. Marine Manager displays and manages observed live data from met masts and wave buoys but also include the forecast data for planning marine operations and aiding decision making.

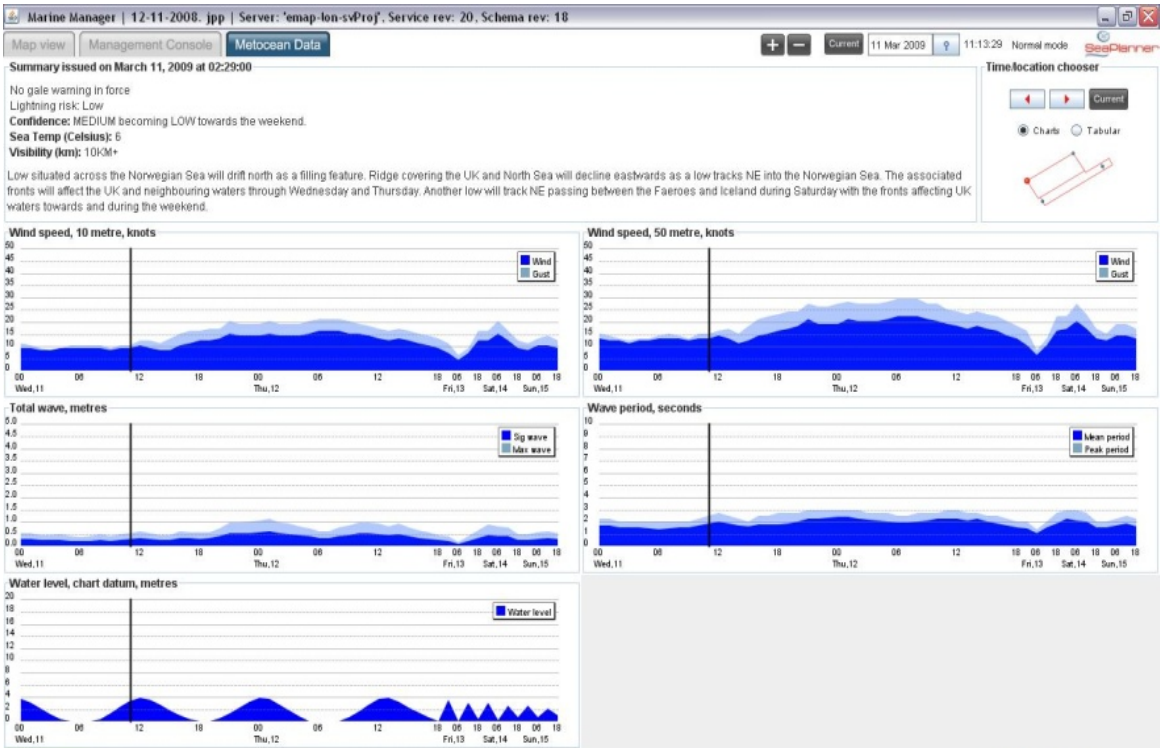


Figure 4 Example forecast output from Marine Manager

Marine operations carried out on Gunfleet Sands site vary from heavy lift operations from large construction vessel to deployment of fast access vessels. During construction there has been up to twenty vessels working on site concurrently. Different vessels and operations have different met ocean constraints attached to safe and successful execution, for example operations involving jack-up barges are significantly constrained by wave period. Users of the forecasts can map the respective operational constraints to the forecast data to determine suitable safe 'Weather Windows' in which to carry out operations.

Marine Manager has allowed multiple stakeholders on the Gunfleet Sands site to view and make use of the marine forecasts. Forecasts are accessed via the web application available at all project office locations and offshore with the use of mobile internet technology. An email output updated three times daily is also sent to a pre arranged list of project personnel and contractors working onsite.

The primary users of the Marine Manager system remains the marine coordinators who act as a link between contractors, marine stakeholders and the project team for communications, site control and health and safety. The project team including the construction manager health and safety manager use the operational forecasts for project planning and health and safety control. Decision making on specific operations is ultimately with the vessel masters and the contractor which underlines the importance of dissemination of consistent data in a common interface.

Validation of wave forecasts in the Outer Thames Estuary

The accuracy and reliability of the forecasts is of vital importance to the planning of operations at the wind farm with a range of weather sensitive marine operations taking place. The marine forecasting service for the Gunfleet Sands Offshore wind farm has been operational since August 2008. Through usage over time the marine coordinators have verified that the wave forecast is accurate within a very small margin of error against the measured wave buoy data collected on site. This has given confidence to both project personnel in planning and executing marine operations. In this paper we present the validation of the wave forecasts against measurements at South Knock (www.cefas.co.uk/wavenet). Although this site is several kilometres from the site, provides a good source of validation data for the model in general.

Forecast model time series were compiled for a set of lead time times from 0-½day, in steps ½ or 1 day to 4-5days and the range of statistics summarised in Table 1 computed.

Table 1 Definition of statistical parameters

$$\mathrm{MAE} = \sum |\Delta f| / n$$

$$\mathrm{BIAS} = \sum [\Delta f] / n$$

$$\mathrm{RMSE} = \sqrt{\sum [\Delta f^2] / n}$$

$$\mathrm{SI} = \mathrm{RMSE} / \bar{o}$$

$$\mathrm{StDev} = \sqrt{\frac{n \sum [\Delta f^2] - \left(\sum [\Delta f]\right)^2}{n(n-1)}}$$

$$R_o = \sum [J] / n$$

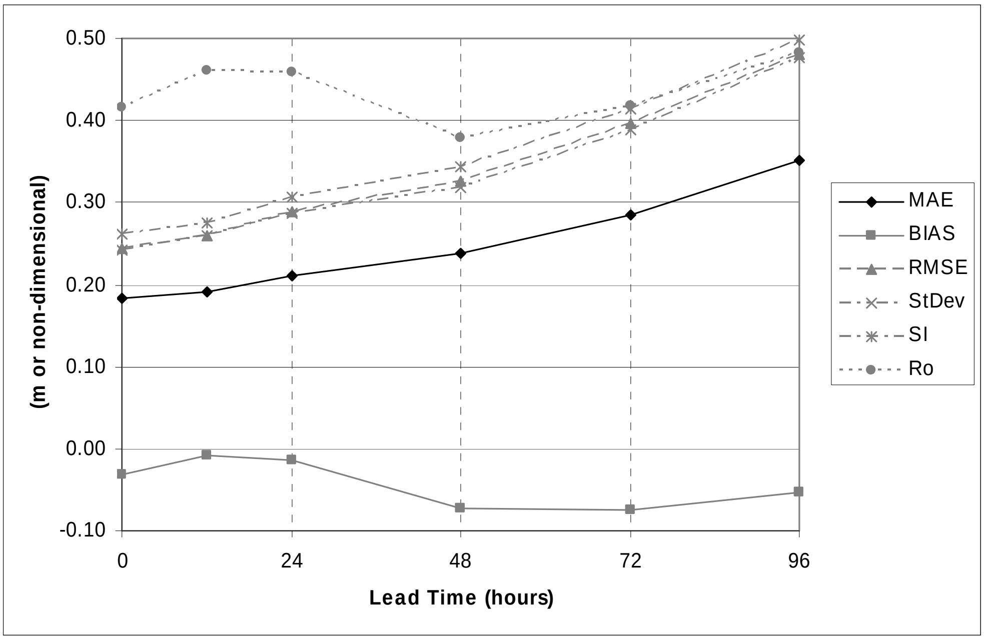


Figure 5 Significant wave height error statistics at South Knock

For a given forecast value, *f*, and corresponding measured value, *o* the error in the forecast, $\Delta f = f - o$. The statistical parameters Mean Absolute Error (*MAE*), Bias (*BIAS*), Root Mean Squared Error (*RMSE*), Scatter Index (*SI*), Standard Deviation of errors (*StDev*), and Over-prediction Ratio (R_o) were calculated for each of the timeseries created. The definitions of the various statistical parameters are provided in Table 1, where: J = 1 for f ⩾ o and J = 0 for f < o, w = weighting parameter, and n = number of data.

Figure 5 shows the error statistics for the period September 2008 to February 2009 for various lead times from 0 to 96 hours. Figure 5 shows that the *MAE* reduces from approximately 0.35m at 96 hours lead time to 0.2m at 0 to 24 hours lead time. Similarly the *RMSE*, *SI* and *StDev* all decrease with reducing lead time. Figure 5 shows that the *BIAS* is always negative, indicating a tendency for the model to underestimate the observed wave conditions, although this becomes negligible with lead times of 24 hours or less. Similarly the R_o which is the proportion of predictions that were overestimates is consistently between 0.4 and 0.5.

Scatter diagrams of forecast against observed significant wave heights are presented in Figure 6 for various lead times. Each graph shows: the forecast significant wave height plotted against the observed value for that time, the one-to-one relationship, the trend line and the coefficient of determination or R-squared value which is a measure how well the trend line fits the data. The figure illustrates the improvement in accuracy of forecasts with R-squared values approaching 0.8 for the shortest lead time.

The differences between the forecast significant wave heights for various lead times are also illustrated in Figure 7. The graphs in Figure 7 show the observed and forecast significant wave heights for times when the wave conditions are relatively severe with maximum significant wave heights above 2m. These graphs show that the general trends are well represented by the longer lead times, providing a useful "heads-up" of conditions and, although never in perfect agreement, become more detailed and accurate with reduced lead time.

Figure 8 shows the wave exceedance curves for the observed and forecast significant wave heights at South Knock. These curves give the overall percentage of time above the range of wave heights, but ignore any phasing errors. The forecast curves show that in general the forecasts and observed exceedance levels are in good agreement. Figure 8 shows for significant wave heights above 1.5m, the forecasts on average slightly underestimate the observed wave conditions for the longer lead time, but this error reduces with the shorter lead time.

(a)

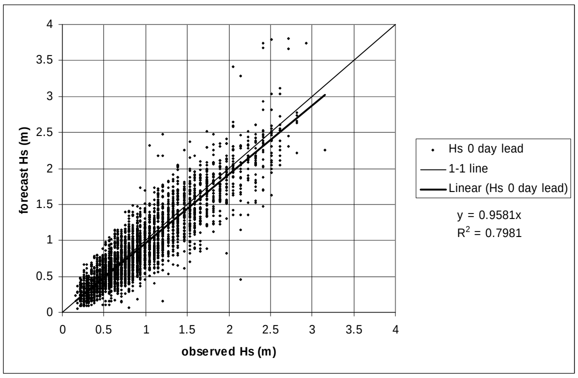


Figure 6(a) Scatter diagram 0-½day lead time

(b)

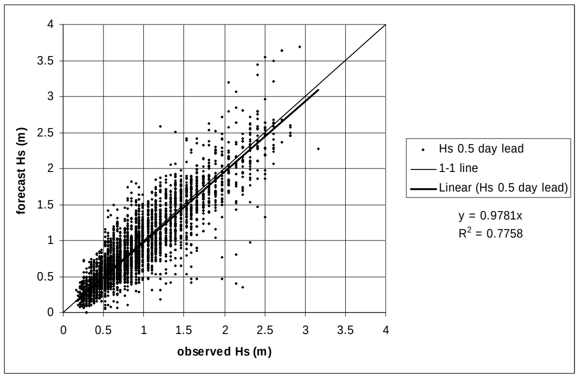


Figure 6(b) Scatter diagram ½-1day lead time

(c)

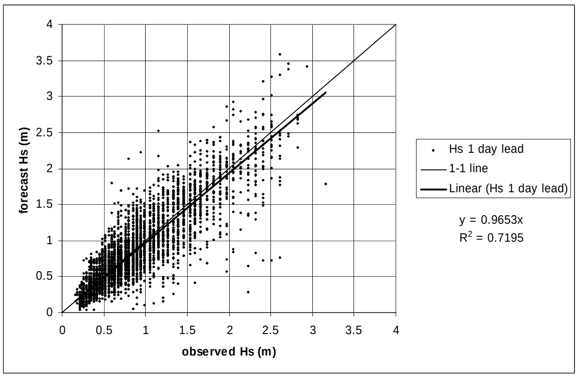


Figure 6(c) Scatter diagram 1-2day lead time

(d)

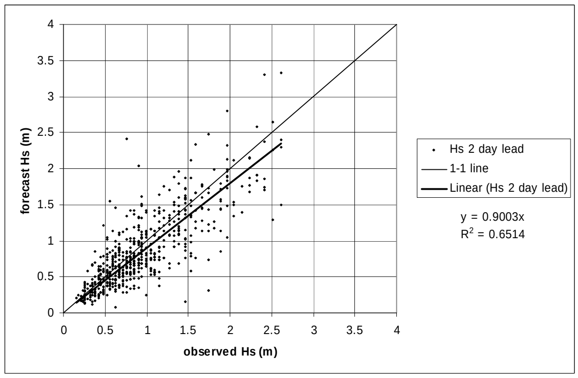


Figure 6(d) Scatter diagram 2-3day lead time

(e)

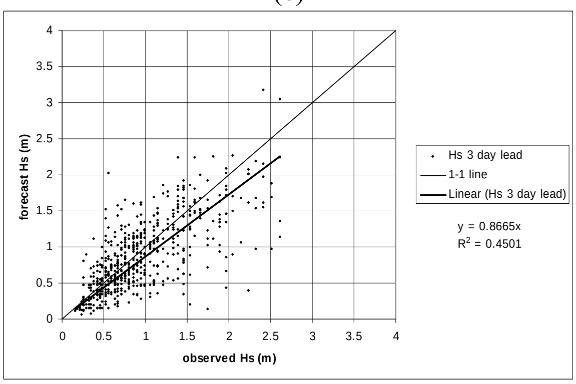


Figure 6(e) Scatter diagram 3-4day lead time

(f)

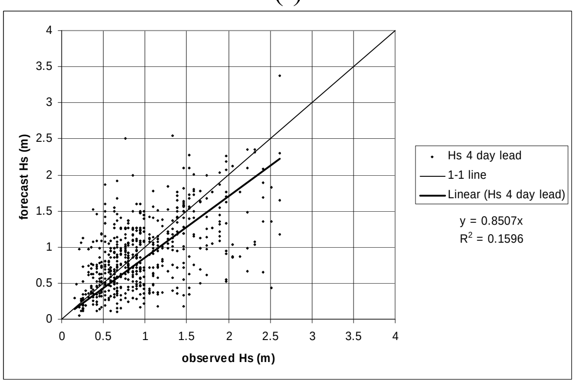
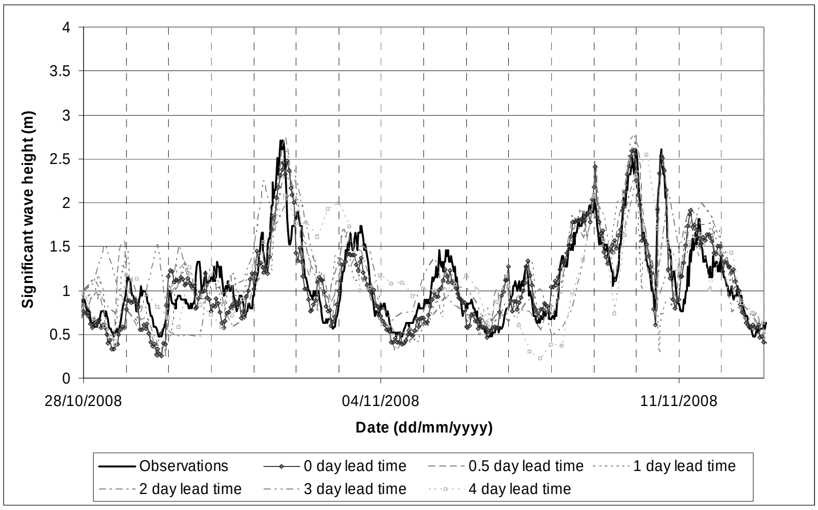
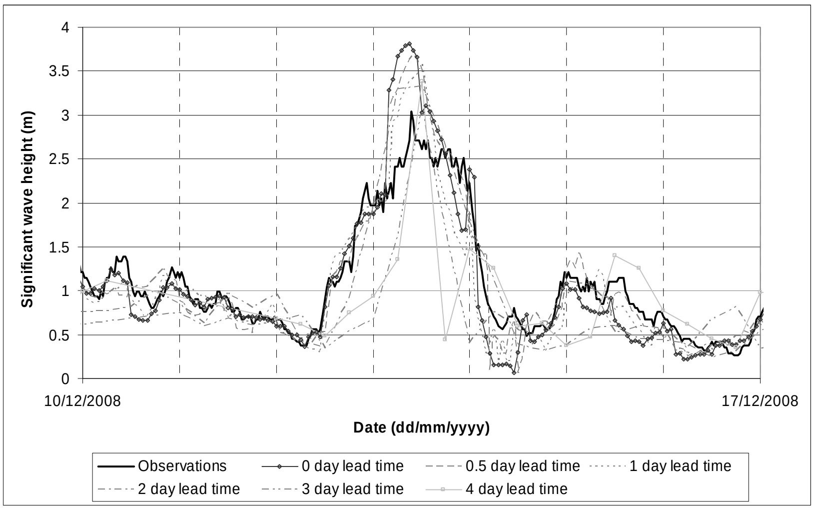


Figure 6(f) Scatter diagram 4-5day lead time



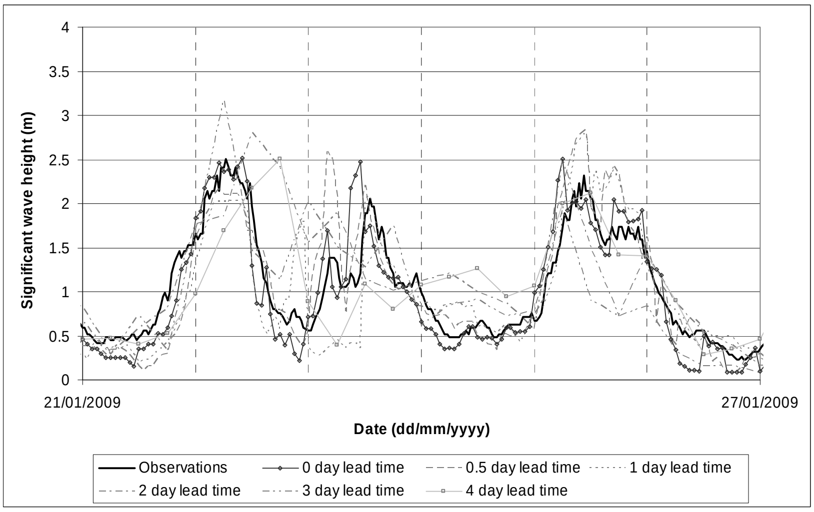
(a)

Figure 7(a) Time series plot (28/10/2008 – 13/11/2008)



(b)

Figure 7(b) Time series plot (10/12/2008 – 17/12/2008)



(c)

Figure 7(c) Time series plot (21/01/2009 – 27/01/2009)

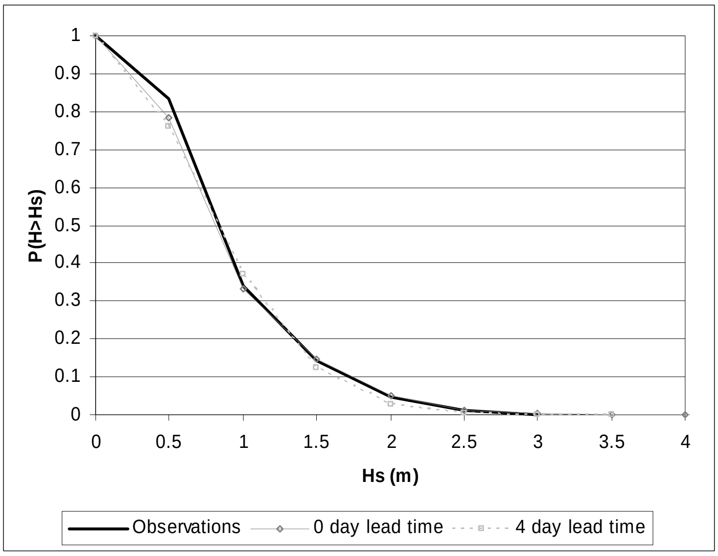


Figure 8 Forecast vs. Observed exceedance curves, for various lead times.

Conclusions and Recommendations

The provision of site specific marine forecasts assists in the management of risks by enabling planning of operations appropriate for impending conditions. There is a requirement for high accuracy in the magnitude and timing of events and timeliness (ability to provide forecasts with sufficient lead time) due to fine lines between safe and unsafe operating conditions.

The Met Office and HR Wallingford have combined their respective skills to develop forecasting systems to provide accurate forecasts in coastal waters where regional models presently do not adequately resolve local features. This paper demonstrates the validity of forecasts of wave conditions in the Outer Thames Estuary.

The availability of in-situ measurements to validate and calibrate models where possible helps to minimise errors in the forecasts. Although historical information is useful, ongoing measurements are important due to continual development of models providing boundary conditions as well as providing useful information for the forecasters.

The presentation of forecasts in a geospatial planning tool that incorporates site specific marine forecasts with associated information regarding vessel position and construction state allows management to make overall planning decisions. Accompanying email and web-based services provide information to the full project team in a consistent way.

For conditions along shipment routes the Met Office also provide forecaster issued route forecasts. These forecasts are based on the Met Office model forecasts, but have the advantage of the Met Office forecaster interpretation by taking into account known model anomalies at a local level. These forecasts allow management of the risk of shipments to construction sites.

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