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Implementation of a wind-farm specific operational wave forecasting tool in the North-Sea: methods and forcing sensitivity

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***Abstract*— The development of marine renewable energy generation from offshore wind turbines has been exponential during the last two decades, along with the need for operational forecasting tools to maintain safe working practise for construction and offshore maintenance teams and for planning maintenance to support improved efficiency in energy production. The principal requirement of an operational wave-modelling tool is to provide forecast wave parameters, in near-real-time, over a discrete windfarm operational area. A balance between model computational time and refinement in the mesh and wave discretisation must be reached.**

The present study presents a 0.5°×0.6° bespoke operational wave model to predict wave conditions over the Greater Gabbard Offshore Wind Farm in the southern North Sea using the finite element Telemac/Tomawac models. To fully capture the tidal effect on the waves, an offline coupling was made between the Tomawac and Telemac hydrodynamic modules. The Tomawac model was calibrated against observations at West Gabbard 2 WaveNet Waverider buoy and model forcing includes wave forcing at the boundaries and wind forcing over the domain. Multiple sources of forcing have been used to calibrate and refine the model to achieve the best performance, assessed by analysis of error statistics in wave parameter prediction. Model computational time was also considered to determine the most suitable forcing combinations for an operational application. The most efficient set up has been implemented on a commercial cloud based HPC cluster, and uses a scheduler to routinely download the model forcing data and initiate the computation. The full operational system will, ultimately, be used by offshore wind farm maintenance providers. The results of the various forcing combinations highlight the importance of accurate and high frequency wind forcing data and the role of the relatively coarse global wave model inputs as boundaries suitable to generate a very effective high resolution operational forecast system.

I. INTRODUCTION

Operational wave modelling to produce near-real time wave parameter forecasts is at present limited to meso-scale, regular gridded datasets, produced mainly by the governmental meteorological services of the coast-bounding countries. Forecasts mostly provide wave-only solutions and do not provide results which include the enhancement of the tide acting on the waves. As a result, significant changes to shape and height of waves, as a function of phases of the tide cycle, are not captured well and the tidal currents are ignored. The accuracy and low resolution of current wave forecasts has several significant cost implications for developers and contractors during both the construction and operational phases of Offshore Wind Farms (OSWF). Ship to platform personnel transfers are prohibited when significant wave heights exceed critical thresholds (which themselves are a function of vessel size) and imprecision in the predicted wave field or the timing of when conditions may change results in costly, abortive ship movements or the loss of operational working time. Currently the largest operation and maintenance cost incurred by OSWF operators is 'waiting for weather' [1]. However, these losses are insignificant when compared with the loss in generating capacity and revenue due to delayed repairs to commissioned turbines and offshore installations.

To improve the information stream informing the OSWF management process, an operational wave forecast is required at precisely the cycle times when go/no-go decisions are made. Greater accuracy in the forecast data is achieved by:

i. Including the phase of the tide by coupling the wave and tide hydrodynamic models to include wave-current interactions.
ii. Providing high spatial resolution and forecast data in precise locations of interest to the client
iii. Providing the forecast data stream at the optimum time in the decision process.

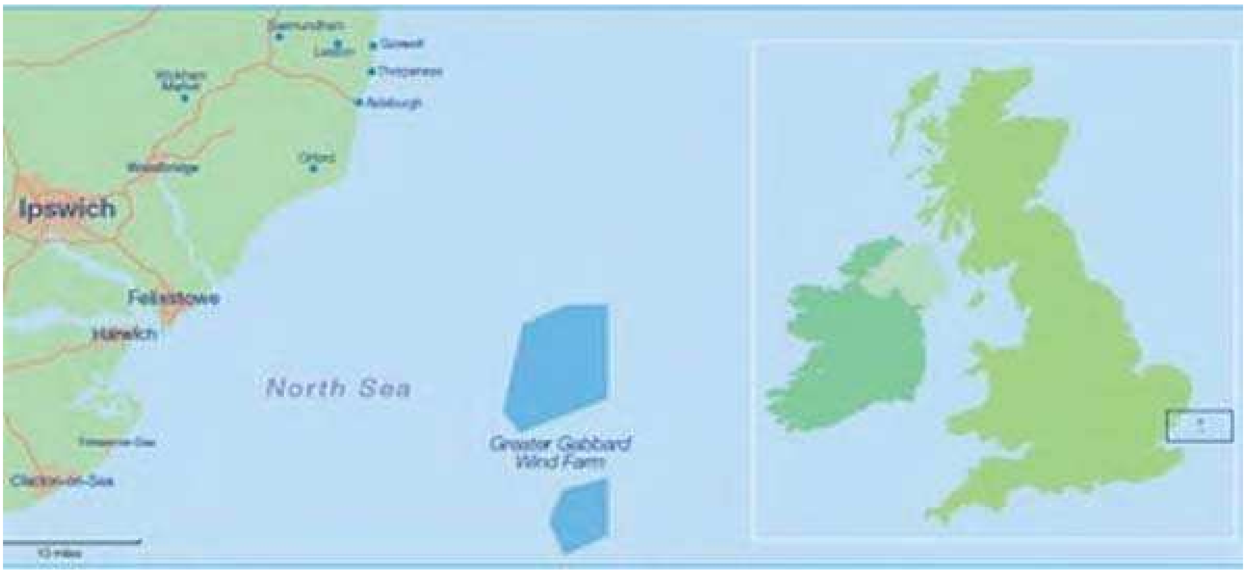


Figure 1: Map of the Greater Gabbard windfarm site in the southern North Sea

The highest resolution of operational wave forecasts available at present is ~4 kilometres, which for general marine information systems may be adequate. However, in the regions of the sandbanks and complex bathymetric features over which the wind-turbines are located, wave models which do not include the effect of tides are less accurate.

The model domain and boundary inputs were specifically designed for the Greater Gabbard site (Figure 1) and the variable resolution of the TELEMAC finite element model enables precise focussing of computational effort to key areas of construction or maintenance operation.
The aim of the project was to initiate and validate an operational wave model for the North Sea Greater Gabbard Wind Farm, producing 48 hour forecasts of significant wave height and peak period including meteorological forcing and wave-tide interactions in shallow water. By increasing spatial resolution over the complex shallow bathymetry and including wave-tide interaction, we aimed to exceed the accuracy of the current state-of-the-art model, operated by the UK Meteorological Office (Wavewatch III, WW3), to predict periods when safe significant wave height working thresholds are exceeded. We achieved this by creating a coupled finite element wave/current model using the TOMAWAC wave and TELEMAC2D tidal current modules of the TELEMAC suite.

II. PROJECT OBJECTIVES

Several objectives were addressed by the project:

- Improve the accuracy of wave forecasts at times when thresholds for wave-height, for the safe transfer of personnel at sea, are approached.
- Provide the data at times coincident with the go/no-go decision path in the operational planning process.
- Design the model domain to provide tailored results which match the complete range physical conditions encountered at the site.
- Enable run-times and results processing to be completed within a pre-defined period, for operational application
- Develop a scalable system with applicability to other domains.

III. MODEL SET-UP

A. *Site location and model domain*

The Greater Gabbard turbine site is situated in the southern North Sea over an area of shallow and complex bathymetry and relatively close to one of the North Sea's amphidromic points. The site was commissioned in August 2013 and now generates up to 500MW from the 140 turbines. The location of the turbine site is shown in Figure 1.

An identical horizontal mesh was used for the TELEMAC2D and TOMAWAC simulations and was designed specifically to work efficiently over the Greater Gabbard wind farm; the boundaries of the model are close to the site border and include locations of the Wavenet Waverider buoy. BODC (British Oceanographic Data Centre) wave and current data sites over the model domain area used to calibrate and validate both models (Figure 2). The mesh has less than 4000 nodes and the bathymetry was derived from UK Hydrographic Office survey data.

The wind over the model domain is fairly consistent, with really small spatial variation. Predicted waves from the WW3 global model are mainly bi-directional, with the predominant directions from the South-West and from the North. This bi-directionality is in agreement with the direction of the largest fetch-lengths.

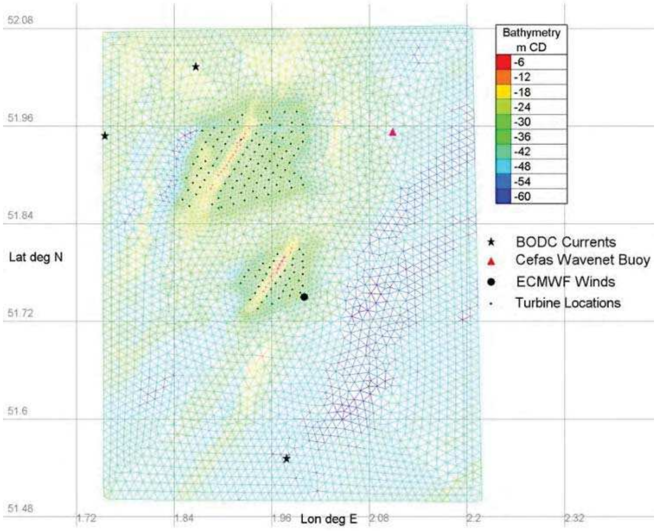


Figure 2: TELEMAC mesh with bathymetry. The small black points locate each wind turbine, large black points the location of ECMWF ERA-Interim forcing data, and black stars the measurement data used over the calibration and validation process. The resolution is refined over the sand banks, where the wind farm is located.

B. *Tidal model*

TELEMAC2D was used to generate the tidal currents over the Gabbard site area, crucial for capturing the true nature of the wave field. The hydrodynamics are forced along the open boundaries using 11 tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4 and MN4) from the OSU TPXO European Shelf 1/30° regional local model.

To transfer the tidal information between the later TPXO large scale model and the Gabbard site, TELEMAC2D options were tested to calibrate the tidal range and tidal velocities.

Wind forcing was first derived from the ECMWF ERA-Interim re-analysis which gives wind data at six hourly intervals with a spatial resolution of 0.125˚. A time-series of wind was then extracted at the domain central point, giving a suitable representativeness of the wind over the small domain due to its small spatial variability. The Met Office's EURO4 model winds are more refined with an hourly interval and a special resolution of 0.04˚. The tidal model was run independently for a 72 hour duration and the results provide tidal velocities to enhance the computation made for significant wave height.

The 22-day-long dataset available from the BODC tidal model results portal (measurement b0010031 measured in November 1978) were used for the validation of the tidal time series (Figure 3). Data were from the Proudman Oceanographic Laboratories, Coastal Ocean Modelling System (POLCOMS), from which model derived outputs have been widely adopted as a resource for tidal currents in many operational marine data systems in the UK. As the mean water level measured at the BODC site with a pressure sensor varied over the survey, we could not use it for the calibration of the tidal water level; however, the simulated tidal period was perfectly in phase with the observations (Figure 3).

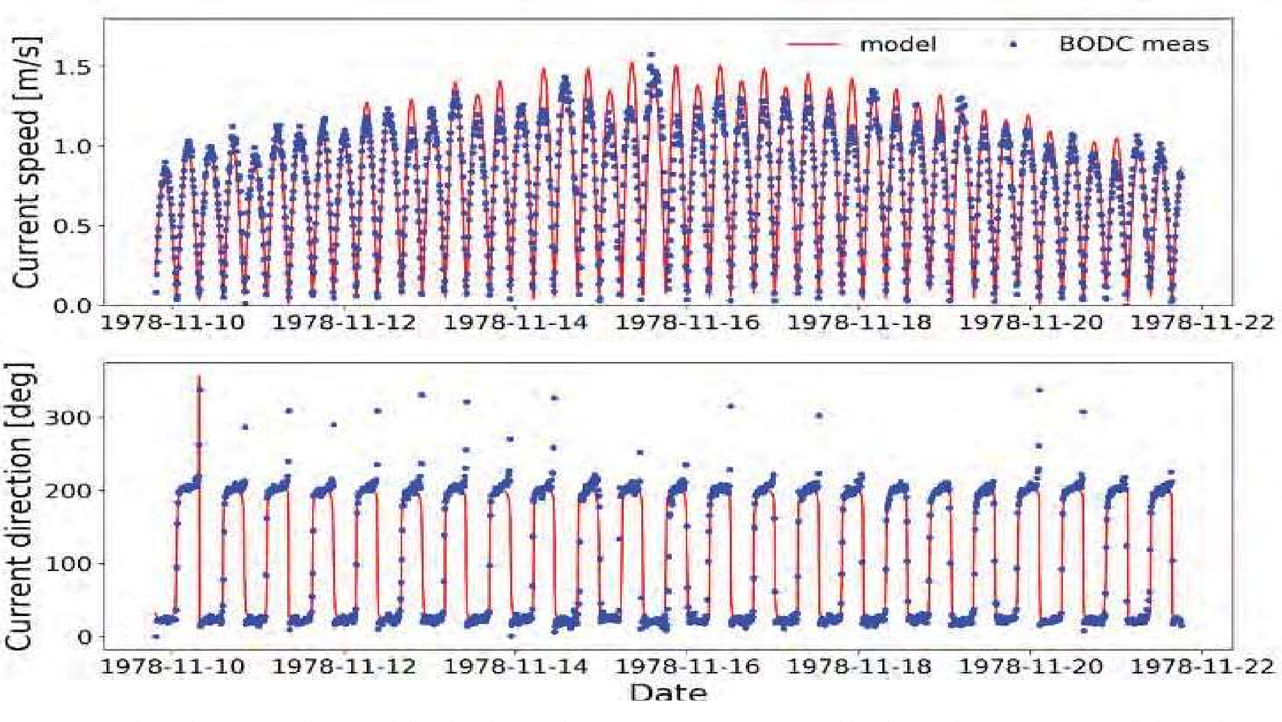
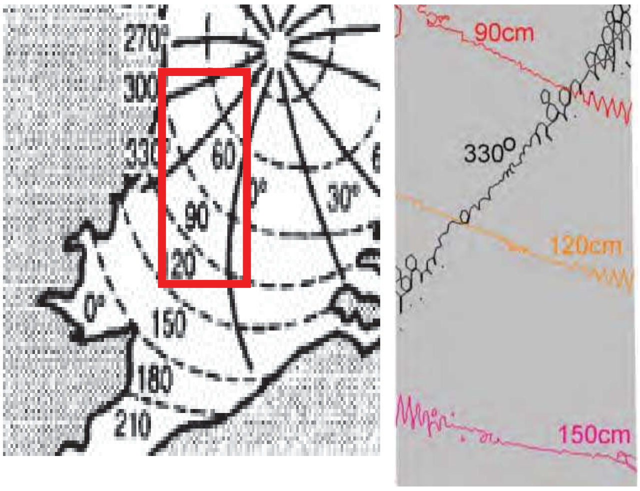


Figure 3: Comparison of current speed (top) and direction (bottom) between BODC measurements (blue dots) and TELEMAC2D prediction (red line)

TABLE 1: TIME PERIODS OVER WHICH THE WAVE CALIBRATION HAS BEEN PERFORMED

Name	What	Time period	Forcing	Location of calibration
A	Predominantly Northerly wind and wave	1 October 2016 until 15 October 2016	From North (lat 52, lon 2.0)	South WW3 location, against WW3 results



a) b)

Figure 4: Comparison of Amplitude and Phase of the tidal component M2 in [2] (a) and in the present model (b). The red rectangle in a) delimits the model domain.

The BODC tidal velocities have been compared with the predictions (Figure 3). The predicted current speed was slightly under-estimated over spring current (strong current) and the average absolute error between TELEMAC2D predicted tidal current and BODC measured data over 22 days is less than 12cm/s, giving a relative error of 16% in the current speed. On average the predicted current direction was off by 11 degrees compared to measurement.

A harmonic analysis of a 30-day duration tidal run was undertaken and the principal tidal component M2 has been extracted (Figure 4). Slight rotation of the predicted M2 co-tide and an amplitude under-prediction with [2] model outputs was detected, but the ranges of amplitude and phase are similar (Figure 4).

As those discrepancies could not be improved by amending both the tidal range and velocity options and the internal physical parameters (bottom friction and water viscosity) in TELEMAC2D and as model tuning for tides can be a very time-consuming operation, the present tidal model was considered validated.

C. *Wave model*

TOMAWAC is the phase-averaging energy density spectral wave model which enables local enhancement of the resolution adjacent to the Wind Turbine Locations, whilst widening nodal density at the bounds of the turbine site. Whilst the UK Waters wave model has relatively coarse resolution our model resolution is increased over the sand-banks and complex bathymetry over which the wind farm was constructed. The model is coupled externally to the TELEMAC2D tidal currents and provides results which include alteration of the surface wave field by the tide which is advecting the waves as they propagate. The wave input data (boundary and initial conditions) are derived from the WWIII model and taken from the nearest points to either the north or southern boundary, depending upon the prevailing conditions indicated in the regional model. This information is read prior to running the initialisation scripts for the model run. Given the

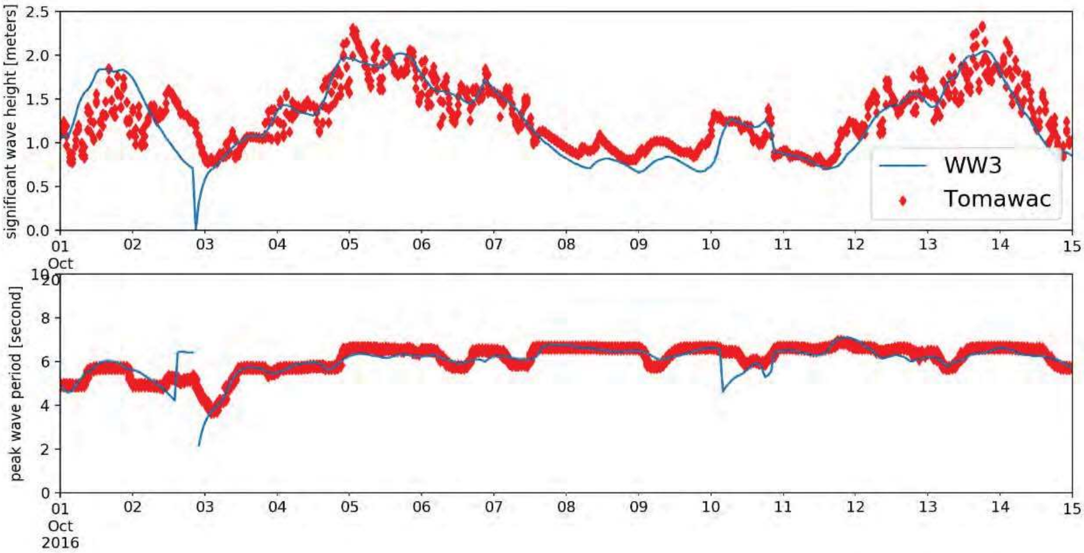


Figure 5: Comparison of significant wave height (top) and peak wave period (bottom) of WW3 model (blue line) and TOMAWAC (red dots)

scarcity of wave forcing, we did not implement a space varying boundary wave forcing.

The physical wave-only processes affecting wave generation and transformation have been calibrated against the validated and widely used WW3 model prediction. A time-period over which the wind was predominantly coming from the North were selected as indicated in TABLE 1. The wave time-series over this period included waves close to the 1.2m-wave-height threshold (Siemens Energy, SSE), above which the transfer to turbine is not recommended for some vessel sizes.

For the TOMAWAC calibration we chose the best performing parameters in simulation A to reproduce the WW3 prediction near the southern boundary using a northerly forcing. As neither TOMAWAC nor WW3 models include tidal effects, both models could be directly compared, and wave-only processes were calibrated.

Over the calibration process, the best wind generation was found using the formulation from [3], that has been used in the cycle 3 release of WAM model [4]. White capping dissipation was best reproduced with the formulation from [5], triad interactions with LTA model and non-linear transfer between frequencies with the DIA method. Bottom friction dissipation was reproduced with [6] and wave growth was limited following the formulation of [7] using the mean of wind sea frequencies. Triad interactions were best reproduced with the LTA model. The Jonswap spectrum was used, completely appropriate for the North sea wave, and the boundary angular distribution following the model from [8] was selected.

The TOMAWAC predicted wave height and peak period (Figure 5) follow the WW3 wave history. Due to missing data in the wave forcing, we cannot rely on the Tomawac prediction over the ~three first days. Some instabilities appear for strong winds, and further development will be needed to adapt the time-step to the wind magnitude.

IV. COUPLING TIDE AND WAVES

D. Coupling method

The initial aim of the project was to provide a direct internal coupling between the tide and wave models such that a precise evaluation of the wave-current interaction would be gained. To meet the requirements for completing the model run in an operational timescale, running in parallel mode was anticipated. However parallel operation has not been used as this would have required an update of the subroutines reading the forcing at the boundary. In Figure 6 the increase of the wave height of up to 0.5m can be seen around the 19th of September when strong (spring) tidal currents occur. The option “strong current” has been tested, but did not result in different wave heights.

TABLE 2:PERIOD OVER WHICH THE COUPLED TIDE-WAVE VALIDATION HAS BEEN PERFORMED

Name	What	Time period	Forcing	Location of validation
Sept	Wave and wind coming from both directions Wind from ecmwf ERA-Interim	September 1st-30th 2016	From both North and South, depending on the wind direction.	At the West Gabbard 2 Site, against measurement from WaveNet

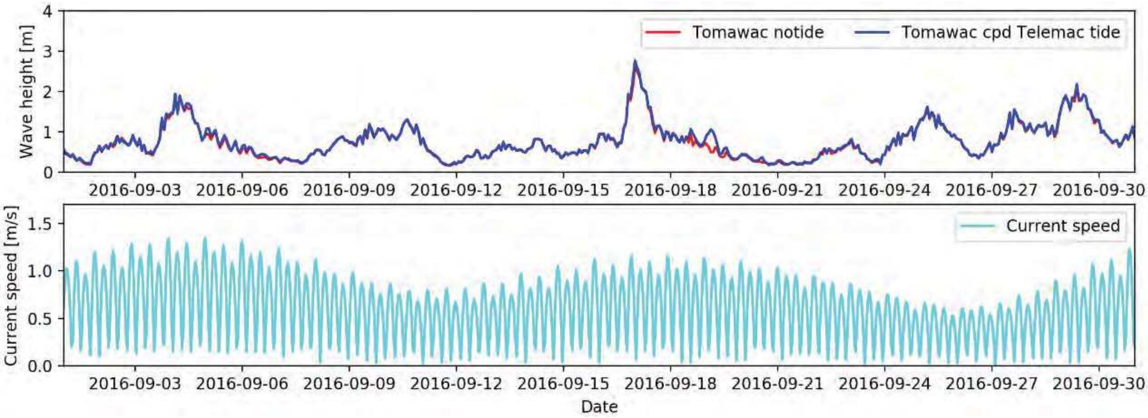


Figure 6: Predicted wave height at West Gabbard site for the uncoupled model (red) and the offline coupled TOMAWAC-TELEMAC2D (blue). The bottom figure shows the strength of the tidal current.

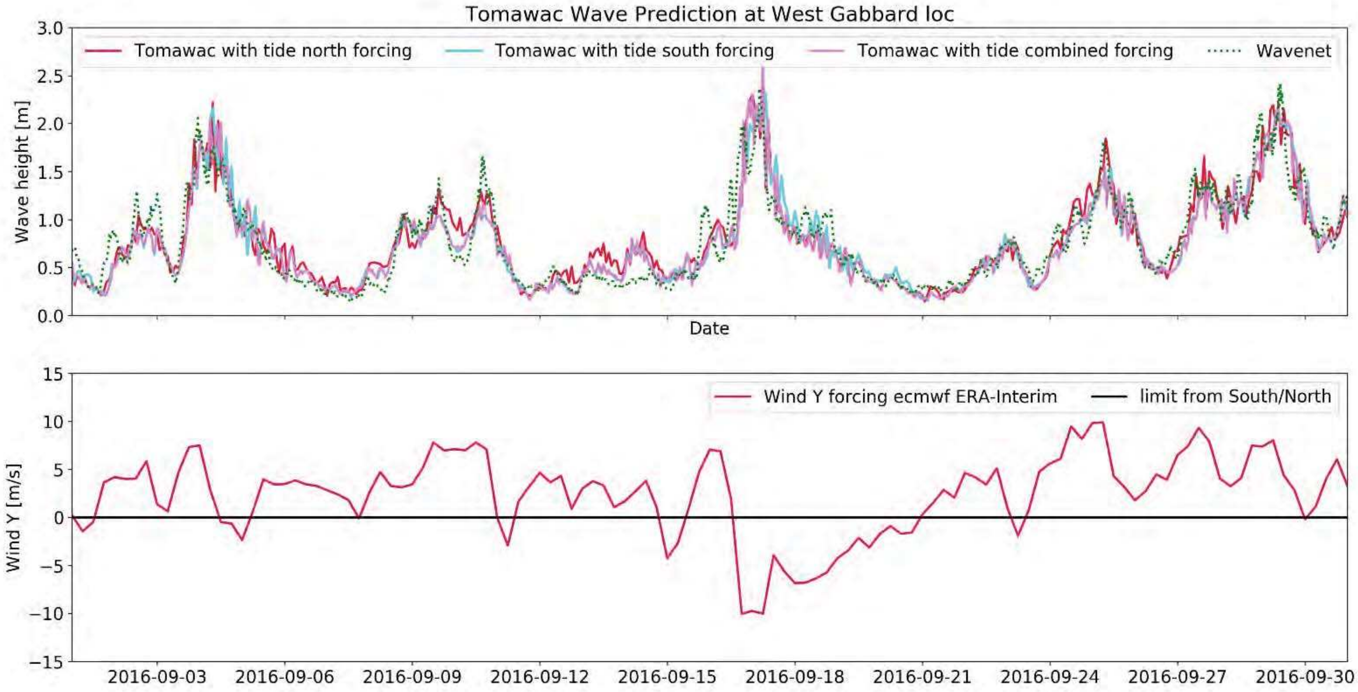


Figure 7: Comparison of the coupled TELEMAC2D-TOMAWAC offline coupled model with wave prediction against Wavenet observations, for three different wave forcings.

E. *Validation of the coupling and sensitivity to forcing condition*

The final calibrated wave-processes-related parameters from the first step calibration (A in table 1) have been used in the simulation "Sept" (Table 2) and the wave forcing has been improved by linking the wave forcing (from Northern or Southern WW3 prediction) with the direction the wind is coming from.

The sensitivity to the boundary wave forcing in the offline coupled TELEMAC2D-TOMAWAC model has been assessed for three simple cases: i) with wave forcing from WW3 North, ii) with wave forcing from WW3 South, and iii) selecting the wave forcing in accordance with the wind direction, i.e. selecting the Northern waves with a wind from the North, and conversely from the South (Figure 8).

The model is improved overall, when the selection of the wave is a function of the wind direction. For example in Figure 8, really good agreement is found for the period 2016-09-11 to 2016-09-14, with the combined forcing as the wind input has been dynamically switched to the Southern forcing data. However, over the period 2016-09-24 until 2016-09-25, EURO4 data indicate a strong wind coming from the North-east, which was not captured in ecmwf ERA-Interm and the combined forcing did not switch to the Northern wave forcing, resulting in an under-prediction of the wave height. We assume that the ecmwf wind temporal-resolution is not high enough resolution, and did not pick-up all the changes in direction. The recent adoption of the EURO4 winds provided to us very recently improves this sensitivity, but results will not be presented in this paper.

To inter-compare the performance of the different forcing configurations, the statistical measures of the error in the prediction with respect to the Wavenet measured data are shown in Table 3 with the maximum error indicated in red and the smallest in green. The "Absolute difference" error (or residual) measures the deviation to the observation. The "Root Mean Square Error" (RMSE) measures this deviation too but is more sensitive to outliers. The "standard deviation" (std) of the error represents how much the prediction varies from the observation. The bias indicates if the model over- or under-predict (respectively associated with a positive and negative

TABLE 3: STATISTICAL MEASURES OF THE ERROR IN THE PREDICTION OF WAVE HEIGHT

Statistical error in wave height prediction	Absolute difference [m]	RMSE [m]	Std	Bias
TOMAWAC with WW3 South forcing	1.310E-01	1.778E-01	1.778E-01	-0.203E-02
TOMAWAC with WW3 North forcing	1.546E-01	1.932E-01	1.887E-01	4.129E-02
TOMAWAC with both WW3 South and North forcing	1.324E-01	1.777E-01	1.776E-01	-0.493E-02
WW3 South prediction	2.270E-01	2.753E-01	2.584E-01	-9.505E-02
WW3 North prediction	1.567E-01	1.949E-01	1.767E-01	3.240E-02

bias). Predictions from the WW3 South model gridpoint are the least accurate and under-predict wave heights (Table 3). The most accurate predictions are found when TOMAWAC is forced with WW3 South model prediction and the model slightly under-predicts wave heights. When TOMAWAC is forced by both the North and South WW3 predictions, it minimises the largest errors (small RMSE and std in Table 3).

V. TUNING FOR OPERATIONAL DELIVERY

As TOMAWAC would not run in MPI mode when forced by a time varying wind and wave input using a fortran user subroutine, the design of the mesh over a small, discrete area became paramount. The models run in scalar mode on the University of East Anglia (UEA) High Performance Computing (HPC) system and computational efficiency is sufficiently good to run the system as an operational service (twice daily), using the most efficient configuration for a future cloud based system.

VI. RESULTS

The developed Gabbard model greatly improves the wave height prediction compared to the currently used WW3 global model (0.5° resolution): the effect of the tide is included and the bathymetry is well reproduced over the domain. The prediction is improved both i) in space with the refined mesh over the wind farm and ii) in accuracy, as RMSE of the predicted wave height is less than 0.18m.

The model can be run as a forecasting tool, and does not require large computing requirements.

The best model forcing consisted of boundary waves forced with the WW3 North conditions, or both WW3 North and South conditions. However, poor time-resolution in free-access wind data leads to the largest remaining uncertainties in wave height prediction, as some rapid change in direction is not always captured in the model. This needs to be improved further in the future development of the model by using other sources of wind data (for example: EURO4 model winds).

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