Met Office

A High Resolution SWAN Model Assessment: North Norfolk to Humber

Forecasting Research Technical Report 557

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Executive Summary

- A high resolution 1km SWAN model has been set up around the North Norfolk coast to assess the Met Office's ability to forecast waves in a complex coastal area where shallow water processes dominate. The output of this model has been compared with the forecast from the Met Office's operational 12km North Atlantic & European (NAE) configuration of WAVEWATCH-III (WW3) covering the same area.

- The 1km SWAN model was forced with UK4 (4km) 10-metre winds and surface tidal elevations from the CS3X SURGE model. Surface currents are not currently ingested as the resolution of the currents in the area is very coarse.

- There are 3 observing platforms in the area - all wave rider buoys - and only 2 of these are covered by both model domains (the NAE domain does not extend as far into The Wash as the 1km SWAN model and therefore does not cover the North Well buoy location).

- Comparison of the model outputs to the buoys observations shows that the 1km SWAN model provides a much improved mean period forecast comprared to the NAE model with a marked reduction in both the RMS error and the large positive bias exhibited in the NAE model. The variability of the mean periods has also been reduced to values more in line with observations suggesting that the poor RMS and bias errors observed in the NAE are not attributed to systematic error only. Improvements in significant wave height RMS errors are negligible compared to the NAE, but there is a small improvement in the bias error. There is also a small improvement to the peak period predictions, but this appears to mostly be constrained to short period cases generated during offshore wind conditions where the extra coastal resolution provides a more accurate fetch length.

- Comparison of fields of mean and standard deviation of sig. wave height, mean and peak periods between the two models reveal that the 1km SWAN model, in general, *reduces* the variability of the wave conditions across the domain. Whilst initially surprising, this does make sense as the higher resolution bathymetry means that more shallow features will be resolved. This will result in a limitation to the range of waves that can exist in these areas (due to longer period waves being refracted away or higher waves being broken) and therefore a reduction in the variability.

- Overall, it appears that the primary shallow water processes in the domain are refraction, shoaling and dissipation. More accurate representation of these processes in the higher resolution SWAN model is the main driver for the improved significant wave height fields. The mean wave period has also benefited from better representation of these processes, but will also see some improvements due to the alternative dissipation scheme employed in SWAN. Triad interactions have not been observed to have a significant effect at this resolution; this means that a similar resolution WW3 model might be tuned to perform with comparable skill in this area (WW3 does not contain triad interactions).

- For future nearshore wave model configurations using SWAN or WW3, two recommendations are made in this report:

  1. Increase spectral resolution to resolve higher frequencies in the tail of the spectrum. This will help to alleviate unrealistic dissipation that can occur in very short fetch growth conditions.
  2. Areas with strong tidal currents may invoke current induced refraction or energy convergence/divergence on the wave field. In such cases it is recommended that a suitable surface current field is ingested.

Contents

1 Background

The Met Office has a number of reasons for wishing to develop improved wave forecasting capabilities for coastal regions of the UK. In particular a commercial requirement to meet the needs of the offshore renewables industry plus ports and harbours, increased uptake of wave products within coastal flood forecasting systems provided through Met Office - Environment Agency systems, and the drive for increased automation of products which places an increased onus on model site specific forecast accuracy.

In order for a wave model to accurately represent waves in the coastal zone, this means three things:

- increasing the spatial resolution around the coast to properly represent the local bathymetric features and variability
- ensuring that relevant shallow water wave processes are being accounted for in the model physics scheme
- ensure all pertinent forcing sources are included and lateral boundary conditions are well specified

Meeting the first criterion is a fairly straightforward; a number of high resolution digital bathymetric data sets (e.g. TCarta (TCarta, 2010)) allow high resolution bathymetric grids to quickly be produced.

Criterion two requires the activation of a number of nearshore wave processes in the model; some of which are quite heavily parameterised in the available numerical schemes. These include parameterisations of processes such as (in a rough order of non-linearity and degree of parameterisation) wave refraction, shoaling, triad (non linear wave-wave) interactions and breaking.

Criterion three acknowledges that in the coastal region the model has to account for several forcing processes. In deep and intermediate water depth (i.e. global and regional wave models) the dominant forcing parameter is usually wind velocity. However, in the nearshore, the effect of the tide can be significant. This can affect the wave evolution in two ways: 1) tidal elevations in the nearshore may be a significant fraction of the overall depth and therefore can have an impact on depth related processes such as refraction and shoaling; 2) tidal currents will affect the propagation speed of the local waves which may result in a Doppler shift in period as well as current related refraction and shoaling in non-homogeneous current fields.

At the time of writing this report in 2011, the Met Office's operational wave model covering the UK area is the 12km North Atlantic and European (NAE) configuration of the WAVEWATCH III ^{TM} model (Tolman, 2007). Whilst this provides adequate spatial resolution to represent the physics and propagation of wave energy for a majority of the northwest European continental shelf, it is too coarse to accurately represent the coastline and variability of the bathymetry in shallow water for a number of coastal areas. A short term solution to this problem is to develop nearshore wave modelling systems that can provide forecasts for specific regions around the UK (e.g. commercially important areas, or areas where we there is a requirement to provide more accurate forcing for other models, such as inundation models).

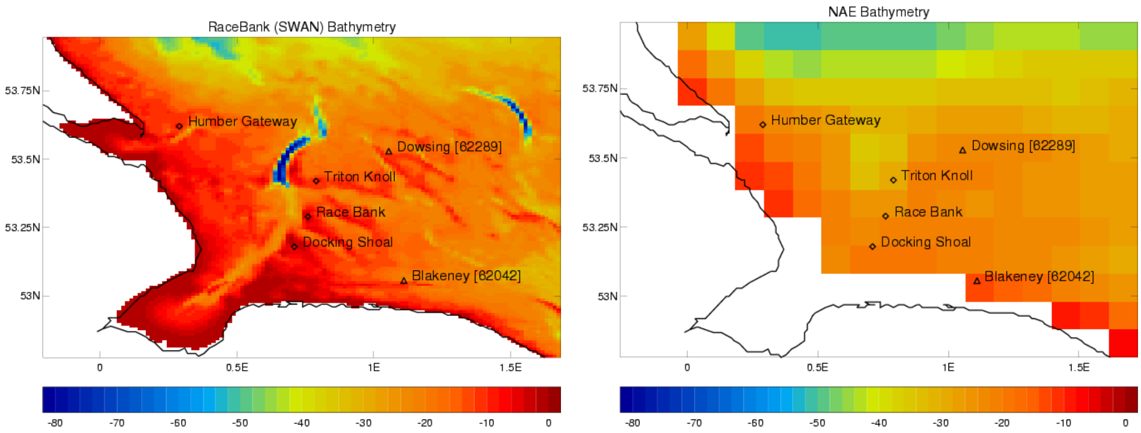
This report details the results of an initial high resolution prototype model set up for an area covering the north Norfolk coast, The Wash and Lincolnshire coast to the Humber. This is an area of relatively shallow water with considerable bathymetric variation which is not well represented by the 12km NAE model (see figure 1). The area contains many shallow banks that are prospective sites for Round 2 and 3 wind farms and is therefore of commercial importance. The area is macrotidal with a average tidal range of $\sim 4-5$ metres. Due to the commercial importance of the area, this study has been funded by the Met Office's Corporate Investment Fund.

2 Model Configurations

To resolve the nearshore bathymetry and account for the relevant shallow water processes, a 1km resolution SWAN model (Holthuijsen et al., 1993, Del, 2010) has been set up to cover the area. SWAN is a dedicated nearshore spectral wave model that parameterises a number of shallow water processes which are either not included in the present release of WAVEWATCH III ^{TM}, or have not been activated in the present NAE configuration. More technical details are given in appendix A.1.

The model is forced with full 2D spectral boundary conditions from a re-run of the operational NAE regional wave model. For this study the spectral resolution has been kept the same as the operational NAE model (25 frequencies and 24 directions), although subsequent to the model set-up a separate study has highlighted a deficiency in the initial growth of short fetch waves that suggests increasing the upper frequency spectrum range could yield further improved results (see section 2.1 and 4.1). The bathymetry for the domain, shown in figure 1(a) was created using a grid-cell averaging method from the 90m TCarta dataset (TCarta, 2010). Wind forcing was taken from the Met Office's UK4 NWP model and tidal elevations from the CS3X SURGE model (Flather, 1976, Flather et al., 1998). Note that tidal currents have not been included in this study.

To provide a comparison, the study simulated a simple post processed product for which the outputs of the operational 12km NAE model are re-gridded onto the same 1km grid as the SWAN model domain. Figure 1(b) shows the resultant bathymetric field. It is immediately obvious from figure 1 that the 12km NAE model does not represent the various banks and channels that are successfully captured in the 1km bathymetry. There is a hint of the deep channel in the middle of the domain in the NAE bathymetry, but the maximum resolved depth is approximately 40 metres, rather than the actual 80+ metres.



(a) SWAN model 1km bathymetry

(b) NAE 12km bathymetry covering the domain

Figure 1: Bathymetries used for the two model configurations. Locations of the two observational buoys (triangles) and some of the more significant banks (diamonds) are also shown.

Figure 1 has also been marked with the locations of some areas of commercial interest (the diamond markers). These are relatively shallow areas that are prospective Round 2 wind farm areas. Note that these are all located on areas of fairly complex bathymetry that is not at all resolved in the 12km NAE model. For instance, Docking Shoal is located in water less than 5 metres deep in places and this is captured well in the 1km bathymetry. However, in the 12km model the location is more like 20 metres deep. This difference in water depth is a significant fraction of the total water depth and will therefore have a significant effect on the successful modelling of the local wave processes at the site.

2.1 Model physics and numerics: SWAN versus WAVEWATCH III

Table 1 lists the physics and numerical approaches available in SWAN and WAVEWATCH III .

Although WAVEWATCH III is designed primarily as a deep water wave model, it does contain a limited amount of shallow water parameterisations, including refraction, bottom friction, shoaling and simple wave breaking. Triad interactions, which are sustained in shallow water and lead to intra-spectral propagation of energy including shifting to higher harmonics of the peak frequency, are not included. A further limiting factor in the use of WW3 in the nearshore is its explicit timestepping scheme which means that as the model grid resolution gets higher, the required advection timestep necessarily gets shorter, as dictated by the CFL criterion. As nearshore wave models often require very high resolution grids the resultant timestep becomes so small that it is no longer economical to run an explicit numerical scheme.

SWAN alleviates some of WAVEWATCH III's numerical restrictions in scenarios requiring a high spatial resolution by using an implicit numerical scheme that is not constrained by the CFL criterion. This makes it feasible to run very high resolution grids with a reasonable amount of resources (e.g. on a modern desktop PC rather than a supercomputer). SWAN also provides a slightly different collection of shallow water wave parameterisations, including features not represented in WAVE-WATCH III such as non-linear triad interactions.

Process	SWAN	WW3
Wind growth	Komen et al. (1994)	Tolman and Chalikov (1996)
Whitecapping	Komen et al. (1994), calibrated by Rogers et al. (2003)	Tolman and Chalikov (1996)
Propagation	1st order, implicit	2nd order, explicit
Wave breaking	Battjes and Janssen (1978)	Battjes and Janssen (1978)
Refraction	yes	yes
Shoaling	yes	yes
Quadruplet interactions	DIA method	DIA method
Triad interactions	LTA method	n/a
Bottom friction	JONSWAP (Hasselmann et al., 1973)	JONSWAP (Hasselmann et al., 1973)

Table 1: Physical parameterisations and numerics used in SWAN and WW3 configurations

3 Verification

The main aim of this study is to ascertain whether the SWAN model can be considered to provide either site specific or areal forecast value over and above the present NAE configuration. The key issue in robustly quantifying this value is the sparsity of observational data, particularly since those data buoys available to the study were found to be located (in moderately deep water) where we might expect the NAE model to perform adequately and the scope for SWAN to demonstrate an improvement is limited as a result. The approach adopted has therefore been to augment the buoy verification with a more qualitative comparison of model performance based on prior knowledge of the bathymetry and an understanding of the wave processes we might expect to be prevalent. This enables a comparison of model output fields in order to identify where the SWAN model is providing extra detail relative to the post processed NAE data.

3.1 Comparison to buoy data

There are three observing platforms located within the area covered by SWAN model domain. These are all directional Waverider buoys providing half hourly measurements of significant wave height, mean/peak wave period and mean wave direction. Observational buoy data is disseminated by the Centre for Environment, Fisheries & Aquaculture (CEFAS). At the time of writing, the period of data available for verification of the model covers November 2010 to March 2011, inclusive. The locations of the observing platforms are show in figure 1(a) and also in table 2 below.

ID	Name	Lat (deg)	Lon (deg)	Depth (m)
62041	North Well	53.059	0.477	29
62042	Blakeney Overfalls	53.057	1.110	18
62289	Dowsing	53.529	1.055	22

Table 2: Buoy locations in model domain

Unfortunately, the North Well buoy is just outside the domain of the re-gridded NAE model and has therefore not been used to verify the models (other than in the Taylor plot in figure 2). This means that only 2 buoys are used to provide verification statistics and both of these are located in areas where we might expect the NAE model to perform acceptably in most situations (i.e. not in *very* shallow water or in the very complex bathymetry area around Race Bank and Docking Shoal). However, the buoy observations allow us to ensure that the wave models specify conditions sensibly when the waves approach the shallow water shoals during onshore conditions and conversely, that the waves are correctly transformed when they propagate over the banks in offshore conditions.

A useful method for gaining a quick overall and comparative indication of how well the two models are performing at the various observation points is to plot statistical data on a Taylor plot (Taylor, 2001) (see appendix B for a brief overview of how to read a Taylor plot). Figure 2 shows verification results for the NAE and SWAN models at the three buoys listed in table 2 (note: only SWAN model statistics are shown for buoy 62041). Three parameters have been plotted for each model - the total significant wave height (diamonds), the mean period (triangles) and the peak period (squares). The overall RMS and bias errors are also shown as a separate table in figure 2. It is immediately clear that the significant wave height predictions are all grouped closely together with good correlation and similar variance compared to the observations; this shows that both models are performing similarly well for that parameter. Peak periods, whilst less well correlated, are also quite closely grouped (ignoring buoy 62041 that is not covered by the NAE model). This is not surprising as the domain is fairly small and the peak period is going to be controlled predominantly by swell propagating in from the boundary conditions supplied by the NAE model to the SWAN model. The most obvious area of improvement in the SWAN model over the NAE model is the mean period prediction. Here is is quite clear that both the variance and correlation of the mean periods are significantly improved. The NAE exhibits $\sim$ 40-50% correlation and $\sim$ 2.0 - 2.2 times the observed variability, whereas the SWAN model performs much better with $\sim$ 70% correlation and $\sim$ 1.5 times the observed variability. This improvement also shows clearly in the mean period biases with the SWAN model almost removing the $\sim$ 1 second positive bias seen in the NAE model.

To complement the Taylor plot, figure 3 shows a breakdown of the RMS and bias errors at each forecast hour. Additionally, figure 4 shows scatter plots of H_{sig}, T_m, and T_p compiled from model and buoy data at buoys 62042 and 62889 (buoy 62041 was not included as it is not represented in the NAE model).

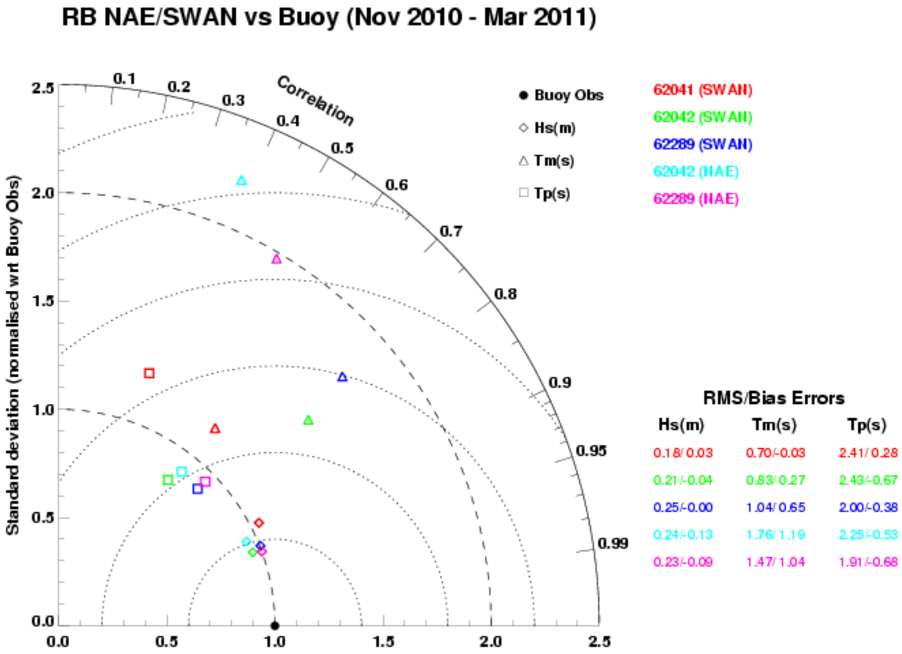
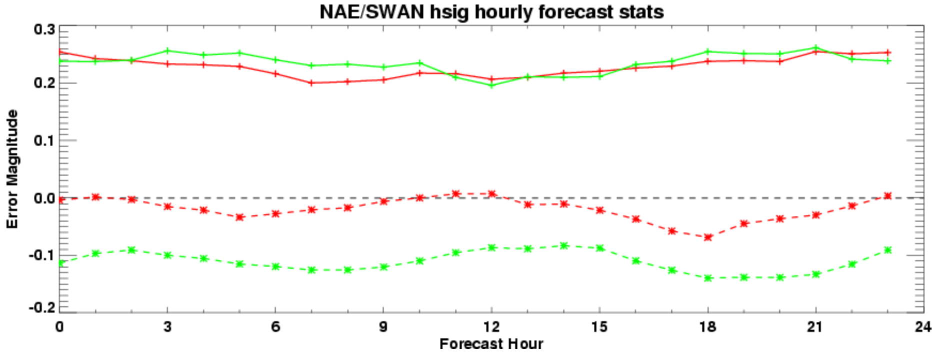


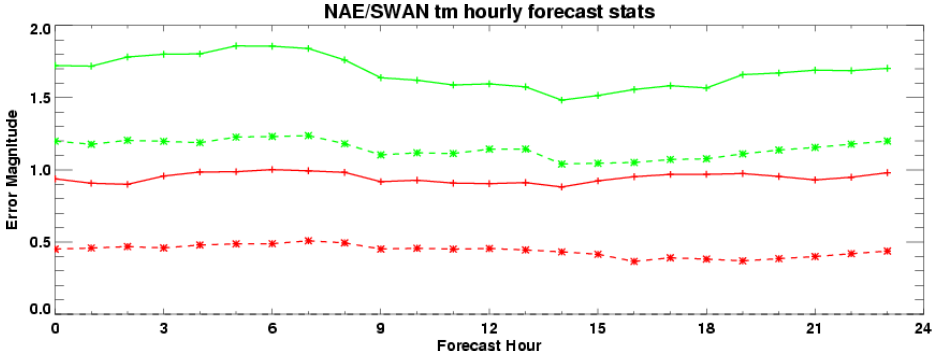
Figure 2: Taylor plot of significant wave height, mean and peak wave period from SWAN and NAE models against observed data.

Figure 4a shows some small improvement in H_{sig} with small reduction in the negative bias present in the NAE throughout the forecast range (see fig 3). This is mainly due to the improvement in the very small wave heights (< 0.3 metres) in the SWAN model (figure 4a). However, the amount of scatter for wave heights greater than this does not appear to be significantly improved. A clear improvement is evident in the T_m forecast with a marked reduction in the RMS error and positive bias seen in the NAE model (figure 3b). The improvement is better for the shorter period waves ($<\sim 5$s) than the longer waves (figure 4c). This is likely due to events with longer period waves being associated with incoming swell from the NAE model. Such waves are likely to have low wave heights and therefore low steepness and, other than encountering some refraction, are likely to propagate to the buoy locations with little change. The same is true for the peak period plots which show a small improvement for shorter periods, but no significant change for longer periods. Due to the buoy locations, it is anticipated that the SWAN model will provide the most extra value over the NAE when the wind conditions are generally offshore. In this case the short fetch lengths of the region are well resolved and the waves will be generating and propagating over shallow and complex bathymetries, such as around Race Bank and Docking shoal, before encountering the observing platforms.

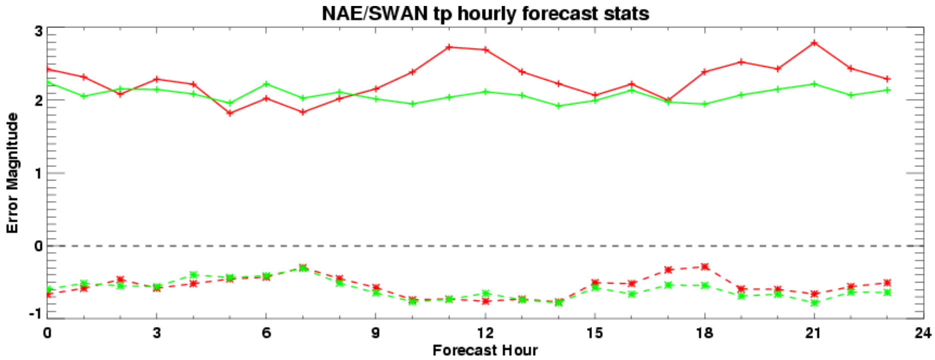
To try and differentiate these onshore and offshore wind generation cases, two extra sets of scatterplots have been produced. Figure 5 shows verification stats where the mean wave direction at



(a) Sig. wave height (metres)



(b) Mean wave period (seconds)



(c) Peak wave period (seconds)

Figure 3: Forecast hour statistics for both models between Nov 2010 and Mar 2011 inclusive. Key: Red line is SWAN model, green line is NAE model. Solid line is RMS error, dashed line is mean bias error.

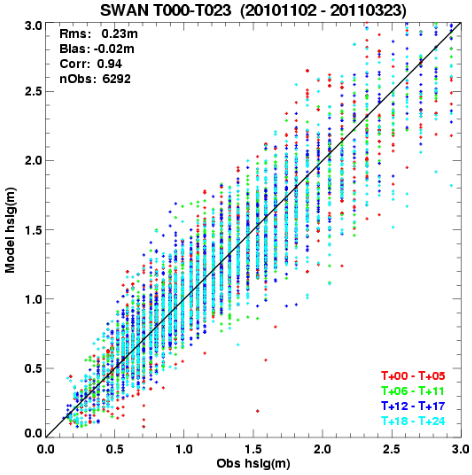
the buoy locations is directed offshore and figure 6 shows the same but for mean wave directions directed generally onshore. Mean wave direction was used to differentiate the results as the observing platforms do not report wind direction or speed. It should also be noted that this is a very simplistic method and in cases where the sea is bi- or multi-modal (e.g. where there is an incoming swell and a locally generated wind sea) the direction is less well defined. However, the results of figures 5 and 6 appear to pick up enough genuine offshore and onshore conditions to make the method useable.

Examining the scatter plots for offshore conditions in figure 5 shows that we have captured mainly waves of shorter period (< 6 seconds), as might be expected in a fetch limited case. Again, it is the wave periods that show the most improvement; the mean wave period has a lot less scatter in the SWAN model and the bias has been significantly reduced. Correlation has improved dramatically too and at least some of this improvement may be due to the SWAN model benefitting from the addition of a tidal elevation input. Figure 7 shows a time series of modelled and observed values during approximately offshore wind conditions at both buoys. It can be noted that there is a clear tidal signal in the observed mean periods of the Dowsing buoy. The NAE model does not capture any of this tidal signal (due to not having a tidal input), but the SWAN model does show some tidal modulation in the mean period (and sometimes the HSig). This is quite evident around the 7th March 2011 in figure 7b. Some of the tidal signal in the observed buoy periods may be due to the Doppler shifting effect of the tidal currents, which occurs when wave encounter rate with a fixed platform changes as waves propagate with or against a strong current. However, as tidal currents are not an input to either model, this effect cannot be captured. This may be an additional improvement added to future configurations.

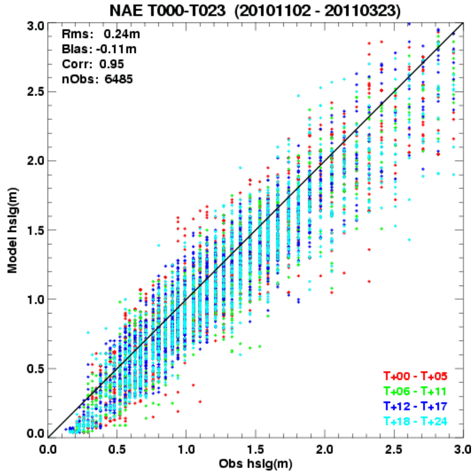
What is also interesting is that in the offshore cases the peak period has also been improved slightly. Whilst this does not show up well in the associated RMS and bias statistics (due to some of the outliers skewing the statistics), the main clustering of points in figure 5 shows improved prediction of peak period in the SWAN model over the NAE model. This is due to the peak period in these cases being linked strongly with the local generation processes of the offshore wind condition rather than being dictated by the boundary conditions provided by the NAE model during onshore wind conditions. Comparing the peak period scatter plots in figure 5 with those of onshore conditions in figure 6 shows this to be the case, since no real discernable value is added by the SWAN model in the onshore conditions.

Unlike peak period, there is a discernable improvement in the mean wave periods during onshore conditions in the SWAN model. Again, there is a marked reduction in the positive bias seen in the NAE model and a reduction in the scatter, particularly in the longer periods ($>= 5$ seconds). This shows that the SWAN model is performing significant transformation of the wave spectra as the waves propagate in from the boundary. Due to the locations of the buoys, this is most likely due to an effect of the whitecapping source terms rather than any dissipation due to shallower water (see table 1 for details of physical parameterisations used in each model).

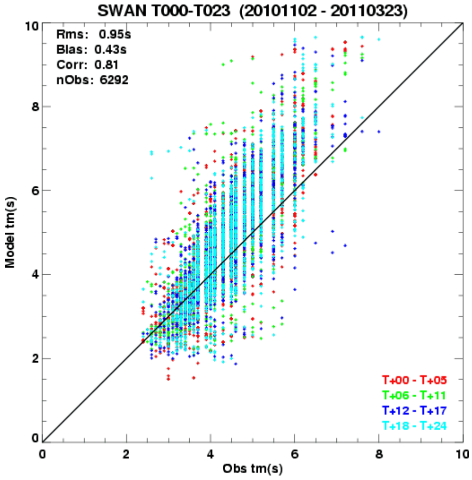
In both the onshore and offshore cases, there is a small improvement to the very negative bias in very low wave heights (< 0.3m) and a small overall improvement in bias in onshore conditions. However, there is a tendency for SWAN to very slightly overpredict the wave heights in offshore conditions (whereas the NAE was generally underpredicting). However, this is in the order of 0.1 metres and the measuring accuracy of the buoy is questioned at this precision (especially at higher wave heights where quite obvious "binning" can be observed in the buoy measurements as bands of similar values).



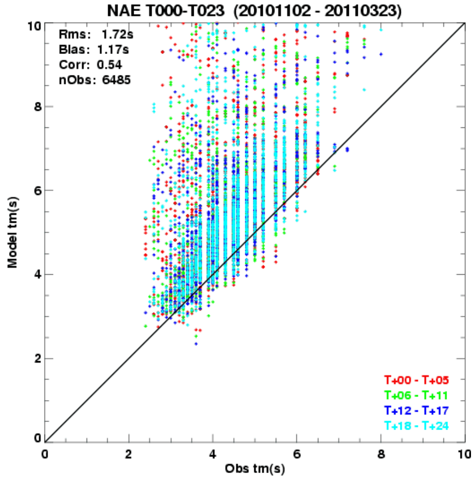
(a) SWAN Hsig



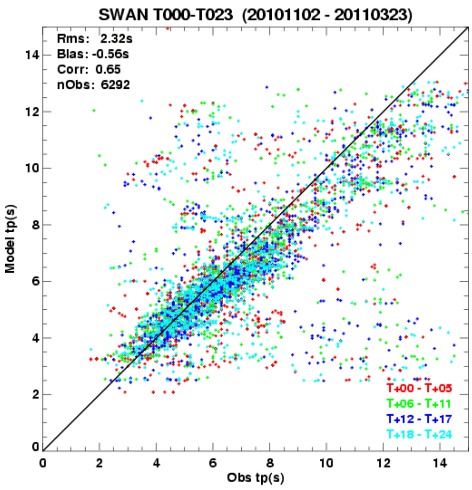
(b) NAE Hsig



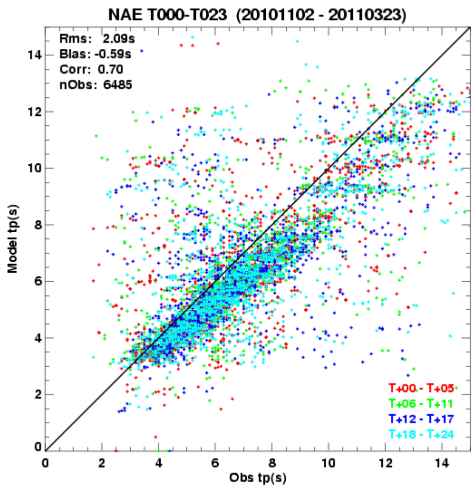
(c) SWAN Tm



(d) NAE Tm

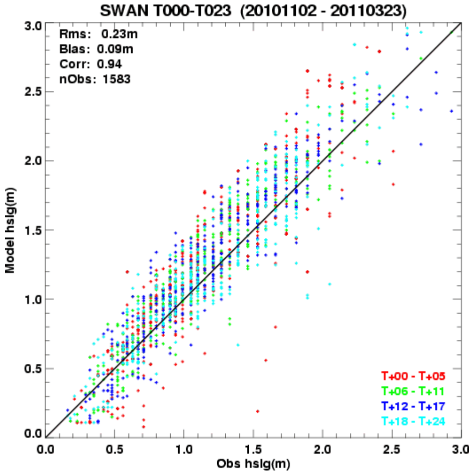


(e) SWAN Tp

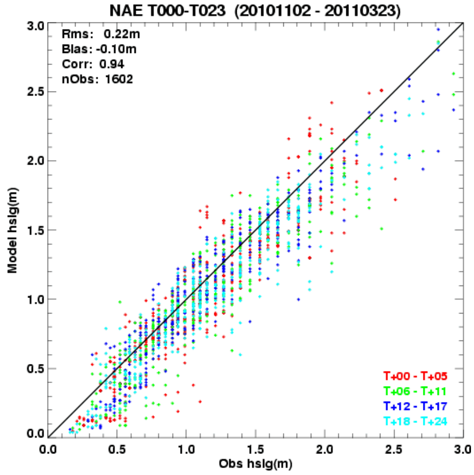


(f) NAE Tp

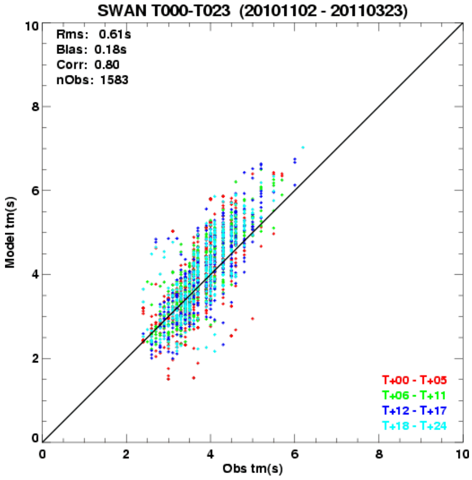
Figure 4: Scatter plots of sig. wave height (top row), mean period (middle row) and peak period (bottom row) for the SWAN/NAE models against buoy observations (62042 and 62289).



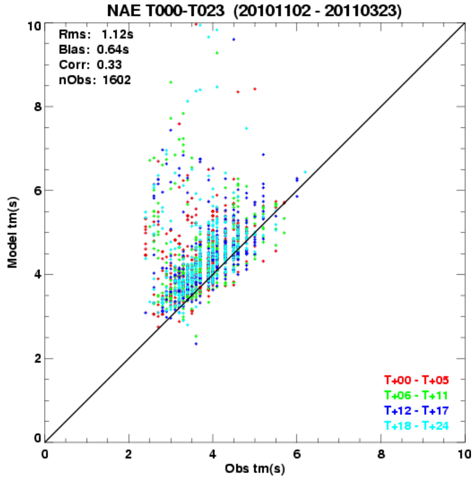
(a) SWAN Hsig



(b) NAE Hsig



(c) SWAN Tm



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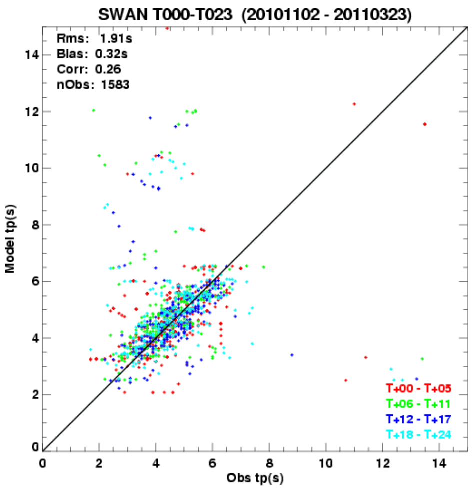
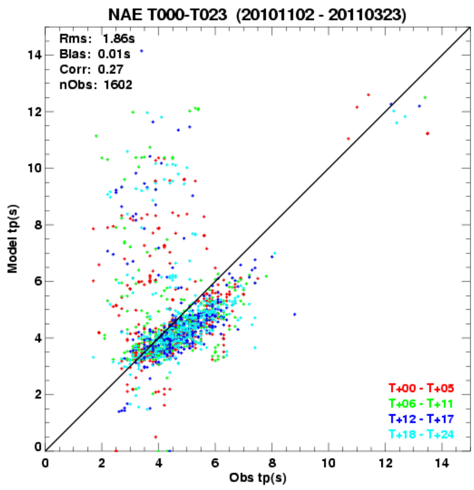
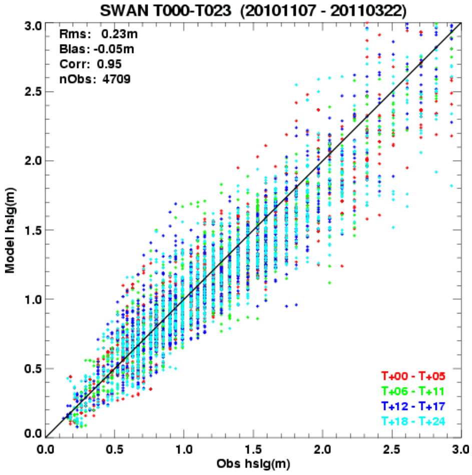


(e) SWAN Tp

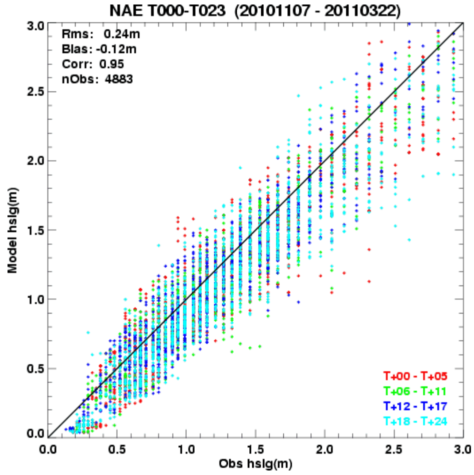


(f) NAE Tp

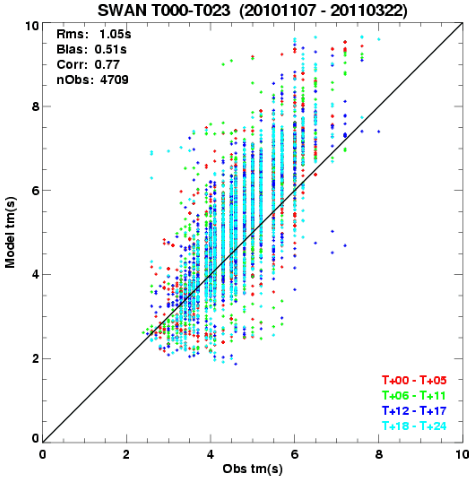
Figure 5: Scatter plots of sig. wave height (top row), mean period (middle row) and peak period (bottom row) for the SWAN/NAE models in approximate offshore wind conditions



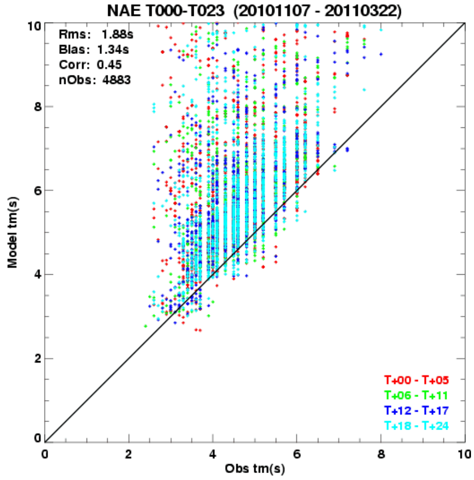
(a) SWAN Hsig



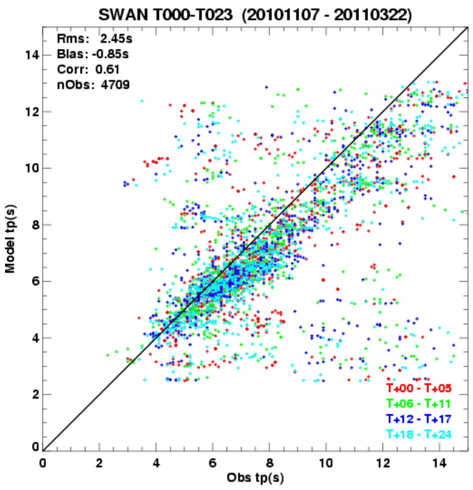
(b) NAE Hsig



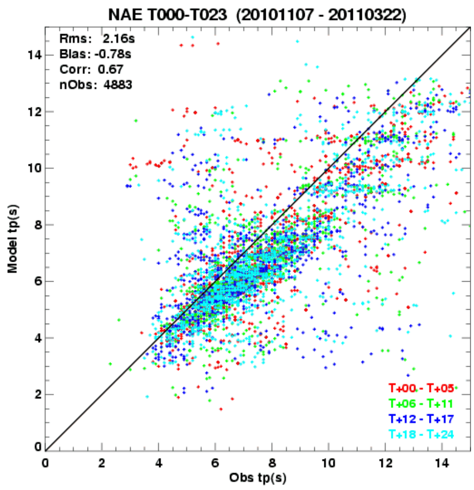
(c) SWAN Tm



(d) NAE Tm

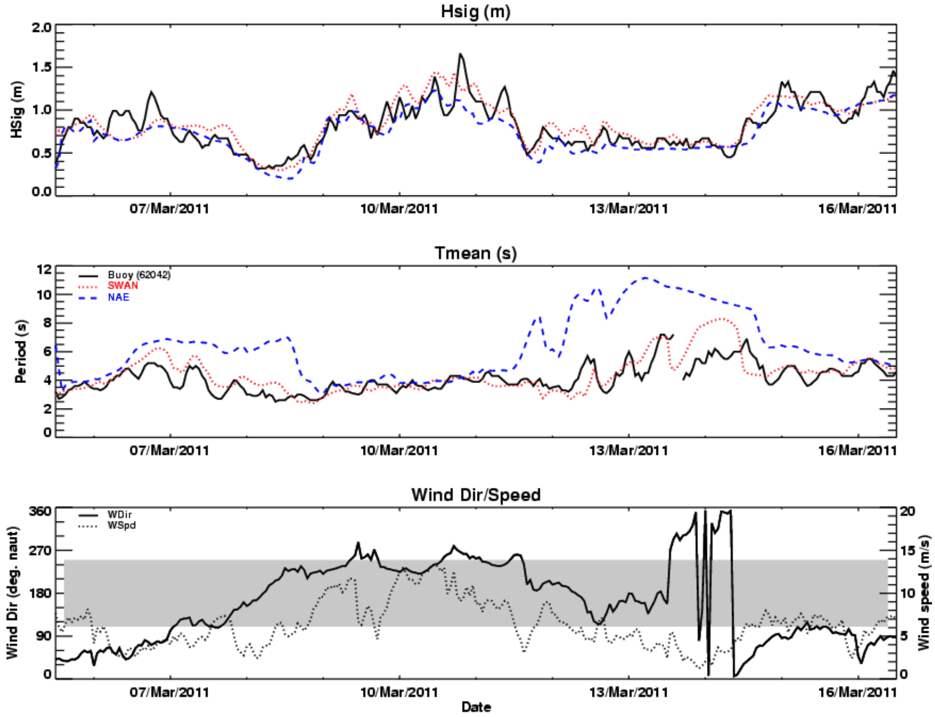


(e) SWAN Tp

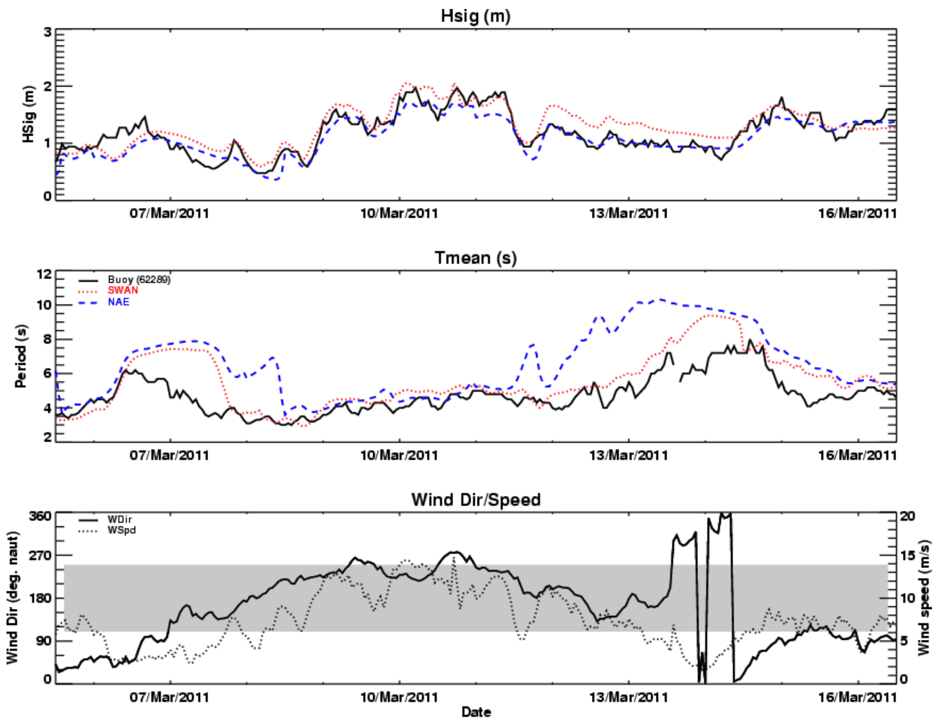


(f) NAE Tp

Figure 6: Scatter plots of sig. wave height (top row), mean period (middle row) and peak period (bottom row) for the SWAN/NAE models in approximate onshore wind conditions



(a) 62042 - Blakeney



(b) 62289 - Dowsing

Figure 7: Model versus observed wave height (top panes) and mean period (middle panes) at buoys 62042 (a) and 62289 (b) in approximately offshore wind conditions (7th - 15th March 2011). Bottom panes shows wind direction and speed. Shaded gray area is approximate offshore wind range.

3.2 Model spatial intercomparison

To compare the spatial representation of wave processes in SWAN and the re-gridded NAE data long term grid point statistics, such as the mean and variance of the significant wave height, were used. It should be noted however that due to the coarse nature of the NAE 12km grid, some near coastal points in the domain are not covered by the 12km NAE grid and are therefore excluded from the comparison.

Figure 8 shows the mean and standard deviations of significant wave height (Hs) compiled from daily forecast data at T+0 and T+12 between November 2010 and March 2011 inclusive. The mean values, shown in panels (a) and (b), indicate that the overall wave energy is grown and dissipated similarly in the two models. The main differences are slightly lower wave heights in the SWAN model over the central deep channel and slightly higher wave heights around and south of Humber Gateway, as shown in panel (c) of figure 8. This is likely due to refractive effects focussing them on shallow areas and defocussing of waves over the deep channel. Similarly, there will be an increased shoaling of waves in the shallow water and decrease in shoaling over the deep trench in the SWAN model.

However, the average mean wave periods (T_m) (figs 9a - 9c) are markedly different between the two models; it is immediately clear that the mean periods are in general lower in SWAN model. The reasons for this are likely two-fold. Firstly, the whitecapping dissipation term in the SWAN model (Komen et al. (1994)) is markedly different from the Tolman and Chalikov (1996) scheme used in WW3. The SWAN model is known to produce mean periods that are shorter than WW3 (too much so in many cases, hence the use of the Rogers et al. (2003) calibration; details in A.1). Secondly, the shallower water in and around the region is well resolved in the 1km SWAN model and this will result in incoming longer period waves being refracted and breaking on the numerous banks in the shallow water. Notice also the slight increase in average wave period near the coastline in the SWAN model. This is most likely due to longer period waves undergoing stronger refraction and shoaling close to the shoreline, particularly in conditions where the dominant wave direction is alongshore.

Figures 8d and 8e show the standard deviation of the significant wave height for the SWAN and NAE configurations compiled from daily forecast data at T+0 and T+12 between November 2010 and March 2011 inclusive. It is immediately clear that the SWAN model is providing much more spatial variability in the wave field. This is obviously a direct consequence of higher resolution grid cells and bathymetric data. What is also apparent is that the variance at individual grid points generally *less* in the SWAN model compared to the NAE model (see the difference plot; fig 8e). The same is true for mean and peak periods (figures 9e/f and 10e/f respectively) with much more spatial detail apparent in the SWAN models, but an overall reduction in variability. The result demonstrates a clear influence of bathymetry on the wave field: the increased bathymetric resolution results in more shallow features being resolved in the model domain and this limits the variety of waves that can exist in those areas due to more waves being broken or refracted away in the shallow regions. For instance the differences in HSig standard deviation shown in figure 8f; the shallow water banks around Docking Shoal and Race Bank show up clearly in the difference plot as areas of significantly reduced variability. This is because the banks are very shallow in that area and more waves will be breaking or refracting away before they get to these points. Hence, only a limited range of short period small waveheight waves will actually exist at those points (the average mean period being about $3.5 - 4.5$ seconds from figure 9a).

Peak period values in SWAN (figure 10) show slightly different behaviour; there is a much stronger correlation with the distribution of the mean and standard deviation of peak period in SWAN with the underlying bathymetry. This is due to the peak period generally being longer (especially in cases where swell is present in the boundary conditions from the NAE model) and therefore interacting with the bottom more than the shorter mean period values. This results in the classic "focussing" effect of the longer period waves on shallow areas and can be seen by a slightly higher average peak period and variance on the shallow banks. The deeper central channel shows a reduction in the average value and standard deviation of peak period as a result of the waves refracting towards shallow water along the edges of the channel, as would be expected.

From this qualitative comparison of the two sets of model fields, it seems clear that there are two physical processes that are dominating the evolution of the wave field and the differences between the models (ignoring the differences in dissipation source terms that are discussed earlier): refraction and shoaling/breaking. The refraction is responsible for focussing/decfocussing longer period waves around banks and troughs respectively. Coupled with this is the shoaling and ultimate breaking of waves on banks due to the shallow water. It is likely the the combination of these two processes, working on a better resolved shallow bathymetry, is at least responsible for the breaking of more long period waves and hence the reduction in overall mean period.

Overall, the behaviour of the high resolution 1km SWAN model in the domain "feels" qualitatively correct with sensible looking shallow water processes occurring in the right places (e.g. swell focussing on the banks and increased dissipation over the better resolved shallow areas). However, as observations are sparse and not available on some of the more intersting banks, it is difficult to judge whether the extra detail and variability that the model exhibits is actually quantitatively correct.

One final point to note is that there is no strong evidence that non-linear triad interactions (included in SWAN but not WW3) are a significant controlling process in this domain; the area appears to be dominated by refraction and shoaling. This suggests that, given the resources, a high resolution WW3 model might perform similarly in the same area, although the differences in the source term physics should be investigated carefully.

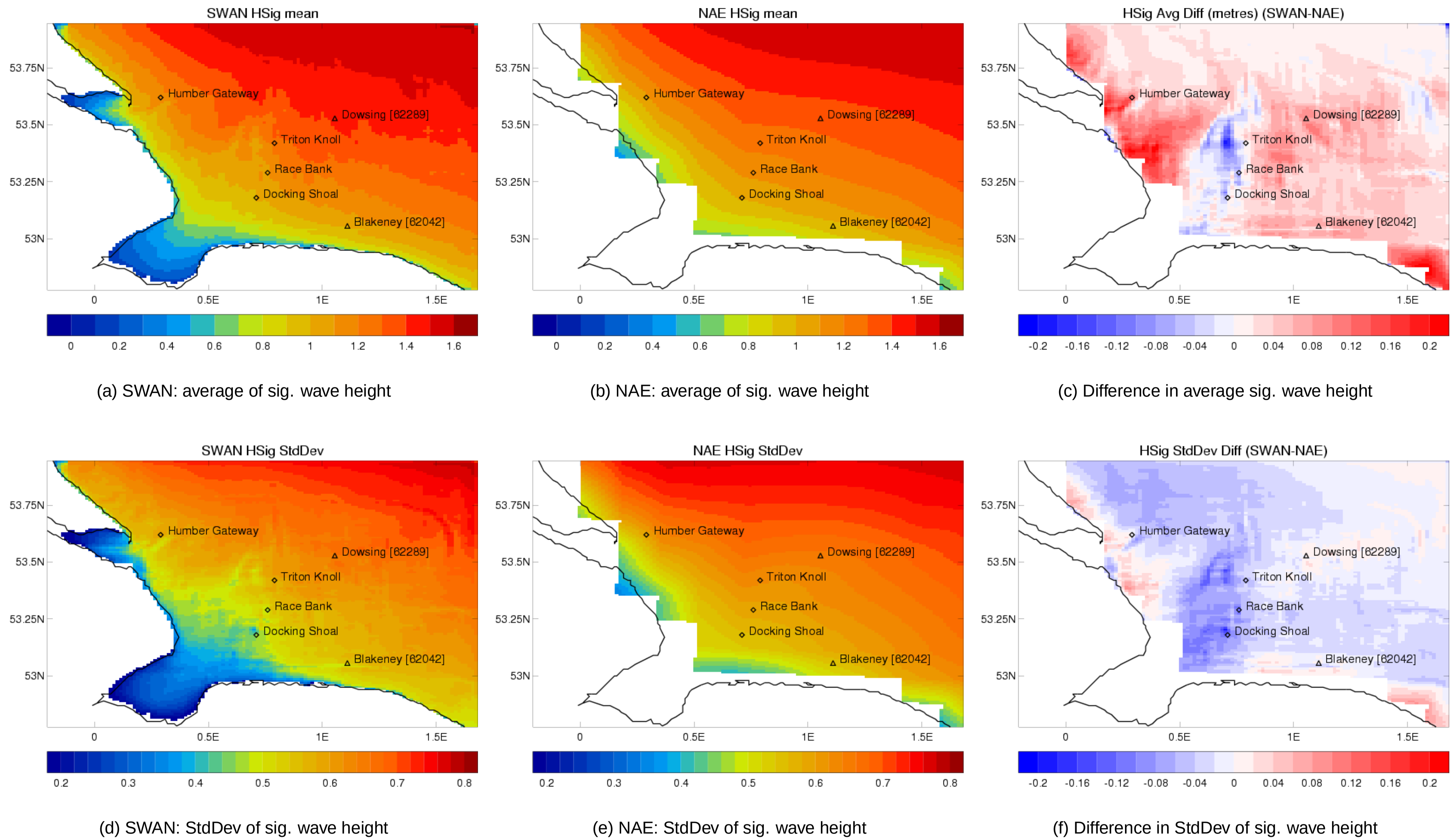
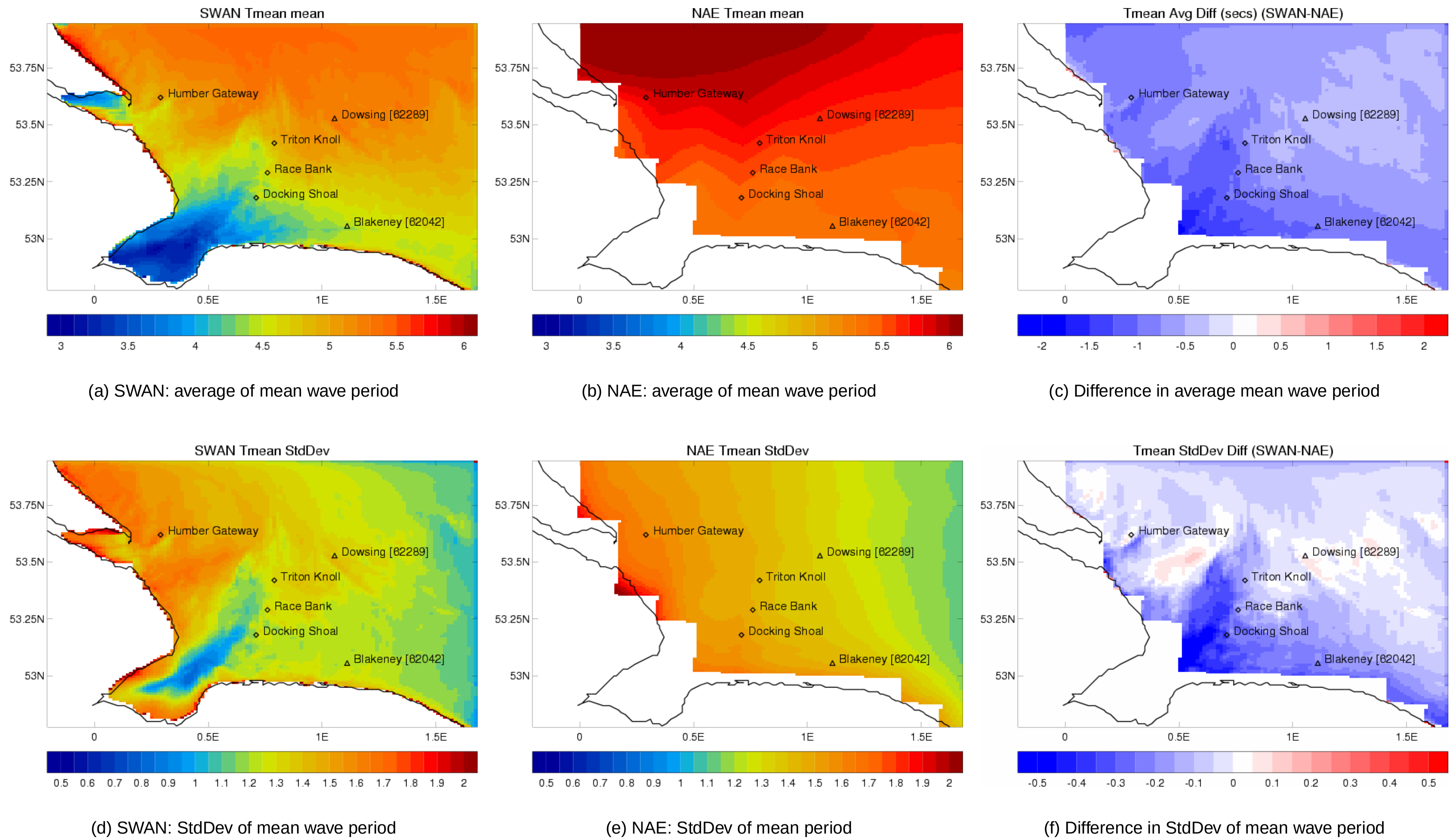


Figure 8: Fields of mean (top) and standard deviation (bottom) for significant wave height from 1km SWAN (left) and 12km NAE (middle) models. Difference in statistics between models (right) is also shown. Diamonds show locations of commercial interest areas; triangles show buoy locations.



(a) SWAN: average of mean wave period

(b) NAE: average of mean wave period

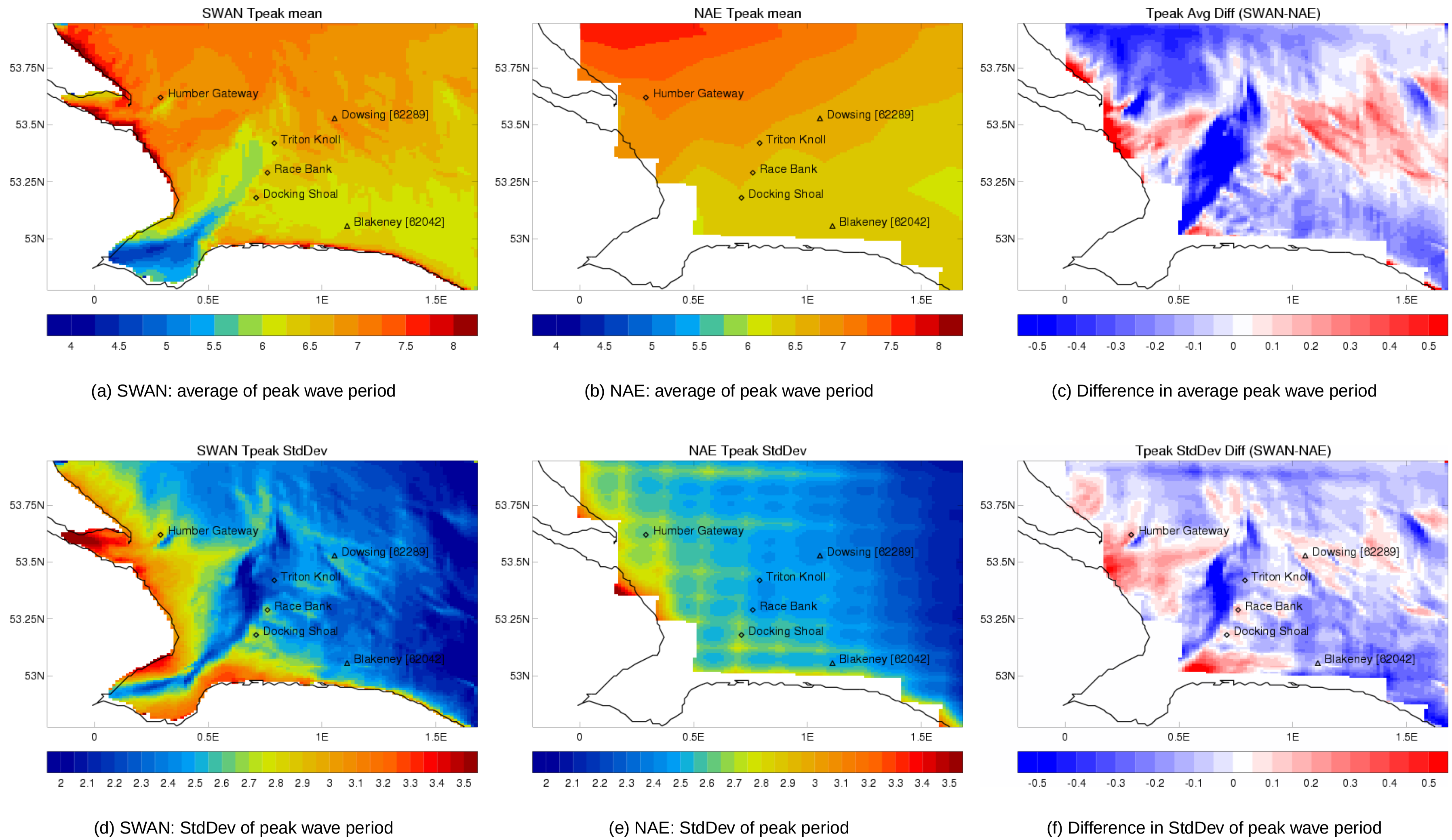
(c) Difference in average mean wave period

(d) SWAN: StdDev of mean wave period

(e) NAE: StdDev of mean period

(f) Difference in StdDev of mean wave period

Figure 9: Fields of mean (top) and standard deviation (bottom) for mean wave period from 1km SWAN (left) and 12km NAE (middle) models. Difference in statistics between models (right) is also shown. Diamonds show locations of commercial interest areas; triangles show buoy locations.



(a) SWAN: average of peak wave period

(b) NAE: average of peak wave period

(c) Difference in average peak wave period

(d) SWAN: StdDev of peak wave period

(e) NAE: StdDev of peak period

(f) Difference in StdDev of peak wave period

Figure 10: Fields of mean (top) and standard deviation (bottom) for peak wave period from 1km SWAN (left) and 12km NAE (middle) models. Difference in statistics between models (right) is also shown. Diamonds show locations of commercial interest areas; triangles show buoy locations. Note that the gridded pattern in the NAE field is an artifact of the interpolation used to regrid the 12km native NAE output to the 1km grid. This issue is exacerbated when regridding the peak period fields as the values are often quite discontinuous between grid cells due to the sensitivity of the peak period to arriving swells

4 Conclusions and Recommendations

From an overall comparison of fields of integrated parameters, it is clear that the 1km SWAN model is providing much more detail in the domain compared to the re-griddded NAE model. The SWAN model also exhibits qualitatively sensible behaviour around the shallow water features such as Race Bank and Docking Shoal where we might expect to see a different wave climate due to enhanced breaking and refraction over the surrounding shallow water shoals. For example, the SWAN model shows an overall *reduction* in the variability of wave heights and mean periods at individual grid points. This can be considered a correct behaviour, since the shallow water features resolved in the 1km bathymetry which effectively limit the populations of waves that can exist on them, i.e. longer period and larger amplitude waves will break or be refracted by the sourrounding shallow water areas. Plots of average peak period also highlight the focussing of the longer period waves on the shallow water banks and coastline with average peak periods being higher in these areas and lower in the deeper central channel. Most of the above improvements can be attributed to the higher resolution bathymetry which enables the complex bed features in the area to be resolved. This results in sharper bottom gradients and shallow water which results in more aggressive refractive and shoaling processes. However, some of the improvements, especially the mean periods, can probably be associated with the different whitecapping physics applied in SWAN. It should be noted that in this study there is no strong evidence that the addition of triad non-linear wave interactions in the SWAN model had a significant effect on the wave field evolution. This suggests that if enough resources are available, the WW3 model (which lacks triad interactions) might perform acceptably if applied to the high resolution domain, although the author advocates the use of a different source term package other than the default T&C96 to achieve comparible mean wave period results.

At the available observation sites it is more difficult to verify that the 1km SWAN model adds significant extra skill over the NAE model for the forecast of headline H_{sig}. Part of the problem is that the two buoys used for comparison are located outside the most "intersting" bathymetric areas (those around Docking Shoal, Race Bank and Triton) in fairly deep water (20m), although they do both have shallow water just inshore of them. We might therefore expect the NAE model to do an "acceptable" job at these points, during onshore conditions. In offshore conditions, although it is anticipated that the SWAN model should perform better (as it will more accurately model the growth and propagation of short fetch waves over the complicated bathymetry inshore of the buoys), generally wave heights will be lower and this will have a quantitative effect on statistics such as bias and RMS error.

Compared to buoy observations, the most obvious improvement in the SWAN model is to mean period prediction for which a marked reduction in both the positive bias seen in the NAE model and the associated RMS error. The modelled variability is also much more in line with observations. As alluded to earlier, this is most likely partly due to the higher resolution bathymetry correctly resolving shallow water areas and therefore limiting the waves in the area, but also in part a result of the different whitecapping scheme using in the SWAN model physics (Komen et al. (1994) with the relative wave number correction of Rogers et al. (2003)). Significant wave heights have seen a negligible change in RMS error and variability, but have seen a small improvement in bias error. Peak periods remain largely unchanged except in offshore cases where these is a small improvement, likely due to a more accurate representation of the fetch length.

Overall, when compared to the limited observation data, the 1km SWAN model is performing at least as well as the NAE for parameters such as the significant wave height, and usually better for mean wave periods. Additionally, the model shows improvements in wave predictions during offshore wind conditions due to more accurately resolved fetch lengths. The higher resolution bathymetry results in much more spatial variability in the wave parameters and more realistically represents the behaviour that might be expected in the areas of complex and shallow bathymetry. On this basis is it expected that the SWAN model would provide an improved automated forecast compared to the present operational NAE forecast.

4.1 Recommendations for further model development

The following points have been identified as recommendations for future improvements to the 1km model, or to similar nearshore domains set up using the SWAN model:

- **Increase the spectral frequency resolution**. A separate study found that there is a deficiency in the growth of short fetch waves in areas with high resolution grids cells (< 1000m). This manifests itself as sudden and unrealistic dissipation of wave energy resulting in a numerical oscillation downstream. It is thought that this is due to the spectral tail not being sufficiently resolved in frequency space resulting in a sudden shift of energy by the non-linear interactions where it is then dissipated by whitecapping. This appears to be an issue in both the WW3 and SWAN source terms. Increasing the number of frequencies in the spectrum resolves more of the spectral tail and alleviates this effect. It is recommended that future nearshore implementations use at least 30 frequencies.
- **Ingestion of tidal currents**. Whilst tidal elevations were ingested into the 1km model and have been seen to add some extra skill at some points in the forecast, some of the variations in observed period are due to Doppler shifting that is not being captured in the model. In areas where the currents are strongly spatially non-homogeneous (such as in tidal races around headlands), other affects such as energy convergence may alter wave heights. These affects are parameterised in SWAN and could be added in future models, if sufficient resolution inputs are available.

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A Model technical details

A.1 SWAN 1km Norfolk-Humber domain

The model used in this domain is the SWAN (**S**imulating **Wa**ves **N**earshore) nearshore spectral wave model (Holthuijsen et al., 1993, Del, 2010) developed at Delft in the Netherlands. Like many modern wave models that cover anything more than a very small local area, the model uses the phase-averaging approach of representing waves using the wave spectrum. It differs from other larger scale spectral models by:

- including parameterisations for many shallow water physical processes, such as wave shoaling, wave breaking, triad-interactions, etc
- utilising an implicit unconditionally stable numerical scheme for wave propagation. This allows very small grid cells to be used (important for resolving coastal features and bathymetric variation) without a prohibitively small advection timestep due to the implicit scheme not being constrained by the CFL criterion

The 1km SWAN model described in this report uses the following processes and inputs:

- Komen et al. (1994) source terms used (wind input and dissipation). Note: SWAN is known to be underpredict mean wave period due to dissipation in higher frequencies being too weak in the Komen scheme. This is alleviated by the Rogers et al. (2003) calibration that results in stronger dissipation on frequencies further from the spectral peak.
- Driven by 4km NAE NWP winds
- Tidal elevations from CS3X SURGE model (12km resolution).
- First order implicit scheme used (conditionally stable) with 30 min timestep.

A.2 WW3 NAE 12km UK Regional domain

At the time of writing, the North Atlantic & European (NAE) model is the Met Office's operational wave model for European and UK wave forecasts. It is based on the WAVEWATCH-III^{TM} model (Tolman, 2007) that is predominantly used for open ocean wave forecasts. However, recent versions of the model have parameterisations of shallow water processes enabling it to be used in near coastal scenarios. The main limiting factor for high resolution coastal modelling is the explicit numerical scheme that rapidly makes the timestep of high resolution grids very small, thus requiring prohibitively large amounts of resources to run the model.

The NAE configuration uses the following processes and inputs:

- Tolman and Chalikov (1996) physics (wind input and dissipation package)
- 2nd order, UNO advection scheme (explicit numerics)
- Driven by 12km NAE winds and boundary condition from global wave model.
- No tidal input (although can be added).
- Has enough "nearshore" physics to get fairly close to the shore (i.e. refraction, shoaling, breaking), but is limited by expense of explicit numeric scheme. Is also missing some important nearshore physics, especially Triad interactions, that are present in SWAN.

To provide outputs that are comparible to the 1km SWAN model, the 12km fields produced by the NAE are re-gridded using bi-linear interpolation onto the same grid definition as the 1km SWAN model.

B Taylor Plots

A Taylor diagram, an example of which is shown in figure 11 is constructed from the relationship between model standard deviation, reference standard deviation, correlation coefficient and the unbiased mean square error because of its similarity to the law of cosines. Consider a triangle, the correlation coefficient becomes the cosine of the angle opposite the side representing the unbiased root mean square error and the other two sides become the standard deviations. It is more useful when discussing possible uses of the Taylor diagram to normalise the standard deviation of the model output by the reference field since it is desirable to compare several different models and model parameters on the single diagram. To plot a Taylor diagram, the reference field which has a correlation coefficient of 1 with itself, a RMSE of 0 and a relative standard deviation with itself of 1 is plotted on the x-axis, at (1,0). A point in the 1st quadrant represents a model field with certain statistics based on its position. The distance from it to the origin represents its relative standard deviation, the distance between the point and the reference field point is its unbiased root mean square error and the angle a line joined from it to the origin makes with the x-axis represents the inverse cosine of the correlation coefficient. The diagram can be extended to the second quadrant by allowing for a negative correlation coefficient.

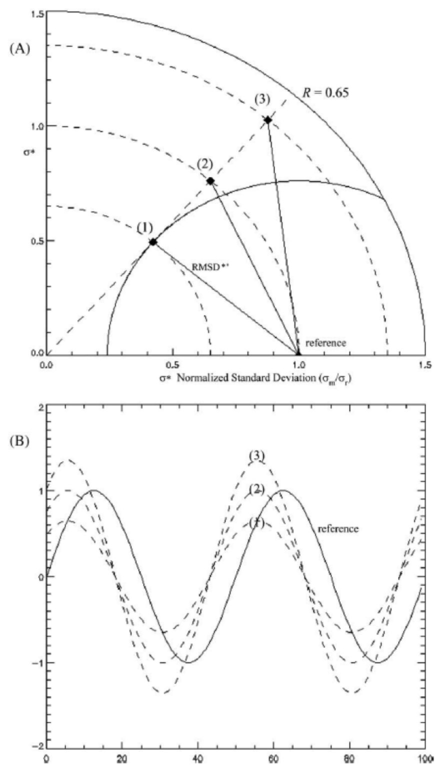

Figure 11: (A) A Taylor Diagram is shown for three model to reference field comparisons where $R = 0.65$ and ratio of model to reference standard deviation is (1) 0.65, (2) 1.0, and (3) 1.35. Three sinusoidal waveforms are plotted to demonstrate the correspondence between the statistics in the Taylor diagram and the actual patterns. Taken from Jolliff et al. (2009)

The purpose of the Taylor diagram is not to simply display one model output against a verification dataset, rather its power lies in its ability to display a multitude of models or model outputs and to make an informed decision as to which particular model performed best and matched the observational data the most skilfully. A skillful model should be able to replicate the pattern of variability as well as the amplitude of the pattern. Both properties can be adequately accounted for by the minimisation of the unbiased root mean square error and the relaxation of the normalised correlation coefficient towards 1. Each of which are ideally resolved by the Taylor diagram, unfortunately it is also important to display information about the bias statistics and to not just minimise the unbiased RMSE at the expense of increasing the total RMSE.

Figure 11 in this appendix displays an ideal case where the difference between reducing the root mean square error by itself at the expense of improving the correlation coefficient can be seen quite clearly. All three diagrams are equally out of phase with the reference pattern and all three lie on a line at the same angle from the x-axis indicating the same value of the correlation coefficient. Model (1) reduces the root mean square while keeping the correlation coefficient fixed. Model (2) has a normalised standard deviation value of 1 and a greater unbiased root mean square error than Model (1) although it does a "better" job of reproducing the pattern of the observation disregarding the phase difference. And Model (3) overestimates the degree of variability just as much as Model (1) underestimated it, it has a much larger unbiased root mean square error as Model (1) but manages to appear to be just as inaccurate as Model (1). The point to be made is that an ideal pattern match or construction of a skill score system should have the property that it nudges the models towards the same ideal normalised standard deviation value of 1 and penalises over- and under-shoots of the normalised standard deviation equally.

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