Met Office

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Evaluating the effects of ocean current fields on a UK regional wave model

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Contents

Executive Summary

Coastal waters surrounding the UK are subject to strong tidal processes. Tidal currents may alter the wave field by affecting the amplitude, frequency and direction of the waves. It is therefore necessary to include these effects in a UK regional wave model in order to improve representation of real world processes and reduce errors. This report details the work carried out to implement and test one way coupling of currents within the Met Office's UK 4km wave model; this upgrade was implemented at Operational Suite (OS) 37 in March 2016.

Three component modelling systems were used in the experiments. Forcing fields for the wave model were provided by an atmospheric model (the Global configuration of the Met Office Unified Model) and an ocean model (the so-called AMM7 configuration of the Nucleus for European Modelling of the Ocean, NEMO). The wave model configuration was based on the 3rd generation spectral wave model, WAVEWATCH III. It is relatively straightforward to include the relevant calculations in a 3rd generation wave model, due to the use of the action density within the model calculations. Unlike the energy of spectral components, wave action is conserved in the presence of an ambient current. A control model run for one year (2012) was first carried out using only the 10m wind fields from the atmospheric model to force the wave model. This was then repeated with the surface current field from the ocean model included in the wave model forcing.

When the output fields of the two wave models were compared there were some noticeable differences, particularly in areas with strong tidal currents, such as the English Channel and Bideford Bay. Wave-current interaction in these areas lead to increased/decrease wave height and changes in the wave period due to a range of processes.

The two models were compared to offshore in-situ data. This comparison showed no degradation of the model performance with the inclusion of a current field. Coastal wave buoys, managed by the Channel Coastal Observatory (CCO), were also used to validate the wave model in relatively shallow (approx. 12m) coastal waters. In some cases there was a discernible improvement in the model RMSE and bias (approximately 10%), when a current field was used. In other areas there was no significant change in the model performance.

Long term wave model performance statistics are dominated by uncertainties in the wind field so, in order to establish whether an improvement in the model performance had been achieved, a case study approach was adopted. A wavelet analysis was used to identify time periods when the currents had a dominant effect on the wave field. This approach identified where the current field had made a significant improvement to the performance of the wave model, particularly when the wave spectra were compared at locations such as Rustington. In other areas, such as Bideford Bay, it was identified that the absence of effects due to changing tidal elevations may still be limiting the accuracy of the wave model.

1. Introduction

A number of previous coastal studies, (e.g.Hothuijsen and Tolman 1991, Ardhuin et al., 2012) have shown the effects of wave-current interaction to be important to the accurate prediction of the wave spectrum. Typically the significant wave height (Hs) may vary by 10-20% due to current effects (Ardhuin et al. 2012). In UK waters strong tidal processes are known to occur and tidal signals can be observed in parameters from wave buoys around the coast. In order to reduce errors in the model around the UK it is necessary to ensure these processes are represented.

The energy of spectral components is not conserved as waves propagate through the current field, due to the exchange of energy between waves and currents via radiation stress (Longuet-Higgins and Stewart, 1960; 1964). However, wave action (action = energy / wave frequency) is conserved and modern 3rd generation models use this quantity, in place of the energy density spectrum, in order to readily account for wave-current interactions in the wave model (Tolman, 2009). Numerous studies have validated the effect of incorporating currents in a wave model (e.g. Holthuijsen and Tolman, 1991; Ardhuin et al., 2012).

Full representation of wave-current interactions requires a two-way feedback between wave and ocean models. Nevertheless, it is anticipated that a significant improvement in representation of the wave field around the UK coast can be made by including forecast currents as a forcing condition for a UK regional wave model. This report documents such a study, in which currents from the Met Office 7km Atlantic Margin Model (AMM7) have been incorporated as forcing conditions into a 4km resolved UK waters wave model.

The report is structured as follows: section 2 introduces the principle processes affecting waves due to their interaction with ocean currents; sections 3 and 4 describe the models used and the study method; sections 5-8 present analyses of the results which, respectively, cover the changes in the wave field spatially, verification of the model in open waters and verification and case studies in coastal waters at sites where tidal effects are most readily identifiable in observations. Conclusions are presented in section 9.

2. Wave-current interaction in coastal waters

Changes in water depth and ambient currents due to tides are known to alter the wave field through a number of processes. The amplitude, frequency and direction of a propagating wave may be altered by a current field (Hayes 1980; Hothuijsen and Tolman 1991). Currents in the ocean are never uniform across stream and therefore changes in the frequency and direction of waves will occur due to the across stream gradients in current speed. A localised effect on the waves due to an ambient current will also occur.

Changes in wave growth and dissipation processes occur where wave energy speeds are altered by the underlying currents. For example, when waves propagate against an opposing current, blocking may occur if the group speed of the waves becomes less than that of the current. In this case the wave steepness will often become large enough to induce larger degrees of wave breaking and dissipation of the wave energy (Ardhuin et al. 2012, Dodet et al., 2013). The speed and direction of a current may alter the effective fetch or the relative effect of the wind speed on the waves. This can lead to higher levels of wind forcing, causing an increase in the wave height and peak frequency where the wind direction opposes the currents, or decreased levels of wind input where wave energy and currents are co-directed.

Current induced refraction of waves occurs through the same process as depth induced refraction: the wave turns towards the area with lower propagation speed of the crest. The wave speed, relative to a fixed point on the sea bed, will be affected by the ambient current as well as changes in the water depth (Holthuijsen 2007). Ardhuin et al., (2012) found that strong currents up-wave of a wave buoy could lead to changes locally at the buoy. In some cases refraction in an opposing current may lead to the formation of extremely high and steep waves due to focusing effects, for example in the Agulhas current (Hayes 1981; Kunze, 1985; Schuman 1975, 1976). Significant modification of the wave field due to refraction is also known to occur in the Gulf Stream (Hayes 1981). In the case of a following current the wavelength will increase and the wave height and steepness will decrease.

3. Modelling System

Experiments were run based on a three component modelling system comprising of an atmospheric model and ocean model providing forcing conditions to a state of the art 3rd generation wave model. Atmospheric forcing data were taken from a (25km horizontal resolution, N768) global configuration of the Met Office Unified Model (UM, Davies et al., 2005). The ocean and wave model components are briefly described as follows.

3.1 Wave Model

The Met Office has used the WAVEWATCH III ocean surface model for all its operational model configurations since 2008. It is a community model initially developed by Hendrik Tolman (Tolman 1991), and now under continual development by the wave modelling community (Tolman and WDG, 2014). The operational Met Office model is based on version 3.14 and operates a second-order advection scheme (Li, 2008) and a rotated grid for the UK 4km (UK4) model used in this study (domain shown in figure 1). Source terms are based on the WAM4 wind input and dissipation package (Janssen, 1991), with the tuning of Bidlot (2012). Boundary conditions are taken from the global 35km wave model described in Saulter (2015).

In the case of no currents the energy of a wave packet is conserved. In the case where currents are included the variance of wave energy is no longer conserved. This is due to the exchange of energy between the waves and the currents due to radiation stress (Longuet-Higgins and Stewart (1960. 1964). Wave action $\boldsymbol{A} \equiv \frac{\boldsymbol{E}}{\boldsymbol{\sigma}}$ is conserved. For this reason the action density spectrum $\boldsymbol{N}(\boldsymbol{k},\boldsymbol{\theta}) \equiv \frac{\boldsymbol{F}(\boldsymbol{k},\boldsymbol{\theta})}{\boldsymbol{\sigma}}$ is used in the wave model (Tolman 2009). This allows currents to be readily included in the model calculations.

WAVEWATCH III accounts for the relative wind effect by using the difference between wind and wave vector velocities (Tolman 2009). The source terms contain parameterizations to address the dissipation of wave energy due to whitecapping, which are generally quasi linear with a coefficient that multiplies the frequency-directional power spectrum. This coefficient is usually proportional to the fourth power of the wave steepness (or can be higher), which will increase in the presence of an opposing current. The definition of steepness varies between parameterizations (Ardhuin et al., 2012).

The effect of currents on wave refraction is accounted for in the propagation and refraction time steps. Changes in frequency are closely related to the Doppler Effect. The frequency of a wave moving in a frame of reference with the current is called the relative frequency or intrinsic frequency (denoted by σ). In a fixed frame of reference, for example relative to the sea-bed, the frequency is called the absolute frequency (denoted as ω). It is related to the relative frequency as (equation 1):

$$\boldsymbol{\omega} = \boldsymbol{\sigma} + \boldsymbol{k}\boldsymbol{U}_{\boldsymbol{n}} \quad \textbf{(1)}$$

Where U_n is the component of the current in the wave direction and K is the wave number (Holthuijsen 2007). In shelf seas, such as the English Channel in the UK, currents and depths are unsteady and inhomogeneous, which means that both the relative and absolute frequency will change (Tolman 1990).

In the case of a current or water depth that varies horizontally and in time, the rate of change of the relative frequency is given by equation 2:

$$\frac{d\sigma}{dt} = C\sigma = \frac{\partial \sigma}{\partial d}\left(\frac{\partial d}{\partial t} + U\frac{\partial d}{\partial s}\right) - C_g k \frac{\partial U_n}{\partial n} \quad \textbf{(2)}$$

Where t is time, d is depth, s is the streamline of the current and n is the wave orthogonal (normal to the crest). The absolute frequency and wave number will change in accordance with the relative frequency as shown in equation 1.

The rate of change of the wave direction due to depth and current-induced refraction is given by equation 3:

$$C_\theta = -\frac{c_g}{c}\frac{\partial c}{\partial m} - \frac{\partial U_n}{\partial m} \qquad \textbf{(3)}$$

where m is the direction of the wave crest.

A form of these equations is calculated using a finite difference approximation in WAVEWATCH III to account for refraction by currents in the model. Model wave periods are output using a frame of reference that is relative to any underlying currents, i.e. the periods reflect wave encounter rates that would be experienced by an object in the water which was also moving with the current

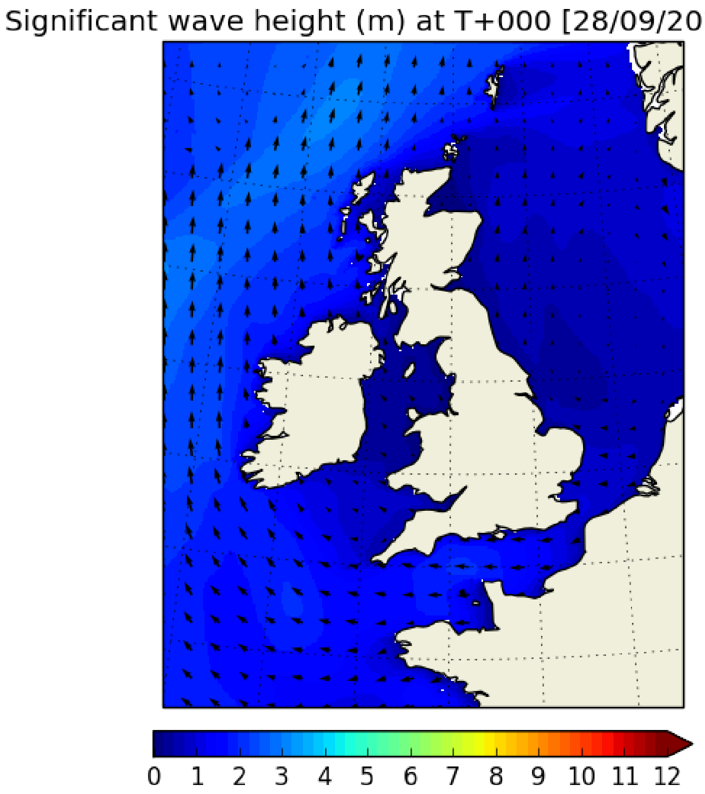

Figure 1 Hs field (m) showing domain of the UK4 wave model in rotated pole coordinates

3.2 Ocean Model

The Atlantic Margin Model (AMM7) is a coupled hydrodynamic-ecosystems model (domain shown in figure 2; see O'Dea et al., 2012, for further details). The model core code is based on the Nucleus for European Modelling of the Ocean (NEMO; Madec et al., 2008). The AMM7 system is run daily and produces analyses and 6 day forecasts of 3D ocean currents, temperature, salinity, tracers and several biogeochemical and optical quantities.

The version of NEMO used by the AMM7 for these experiments was 3.2. Surface forcing for NEMO was taken from the Met Office NWP model and comprised heat and moisture at 3–hourly intervals, and wind speed and surface pressure at hourly intervals. A non-linear free surface is needed for modeling tides and surges, this is implemented using a variable volume and a time splitting method, using 'leap-frog' time stepping, the momentum advection is energy and enstrophy conserving. The lateral boundary condition in the momentum scheme is free slip. Tidal forcing on the open boundary is via a Flather radiation boundary condition (Flather, 1976) and through the inclusion of an equilibrium tide. Fifteen tidal constituents are calculated from a tidal model of the northeast Atlantic which specifies depth mean (barotropic) current velocities and sea surface elevation. Non-tidal boundary conditions are taken from a North Atlantic configuration of the deep ocean Forecast Ocean Assimilation Model (FOAM-NEMO) system.

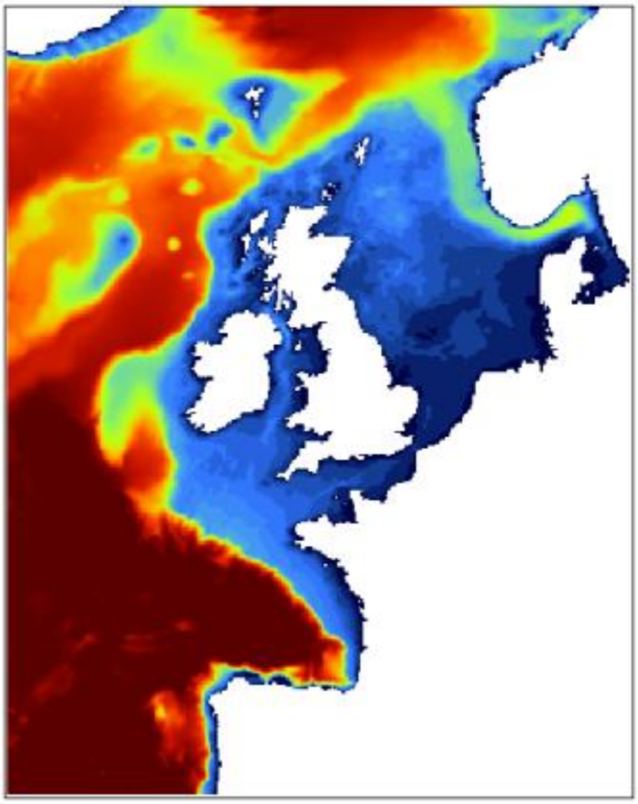

Figure 2 Bathymetery showing the AMM7 model domain.; AMM domain (NOOS Bathymetry) from 40°S, 20°W to 65°N, 13°E.

4. Experiment Set Up

In order to evaluate the effect of currents on the UK4 wave model, a year long hindcast was run for 2012. Global (25km) UM analysis winds were used to force the wave model. The current field was taken from the AMM7 operational hindcast, forced by the same atmospheric analyses. The model was first run without currents as a control; the hindcast was then repeated with the current input field. The wave parameter fields were then compared for the whole domain. This showed where the wave field had been significantly affected by the addition of the currents.

The model outputs were also compared with in-situ observations from the JCOMM wave forecast inter-comparison project (Bidlot et al., 2007) in open shelf seas waters. This 'truth' is used to ensure that a change to the model does not degrade the operational system. The results of this comparison indicated no degradation; however there was also no clear improvement in the model error.

Using data from the Channel Coast Observatory (CCO, http://www.channelcoast.org/), coastal wave buoys where a strong tidal signal could be observed in the wave parameters were used to validate the effect of the currents on the wave field in nearshore areas. A case study approach was used to identify time periods when the effect of the currents on the wave field was the predominant forcing field. This allowed the performance of the wave model forced with a current field to be evaluated in more detail.

For studies of real-world conditions one of the challenges faced, when validating the introduction of a current field to a model, is identifying locations and instances where the currents affect the wave field to a similar (or larger) extent than variations in the wind field. Wind induced modulations in the wave parameters, over a similar time scale as those caused by tides (approximately 12 hours), often make it difficult to analyse the extent of the modulations due to tidal effects alone. This in turn makes it difficult to validate the performance of a wave model that is coupled to a current model. In this study a wavelet analysis is used to address this problem. Details of the wavelet method are given in Palmer et al. (2015).

While the wavelet can be used to identify power in the time series at approximately the same frequency as the diurnal tidal signal, it is not possible to be sure that the modulations are due to the effects of the currents alone. It is possible that the tidal signal in the wave parameter time series is 'contaminated' by variations caused by fluctuations in the forcing wind at the same frequency. However, events where the wave signal was strongly affected by tidal currents could be identified by comparing wavelet signal power at the 12 hour (semi-diurnal tide) period from the model runs with and without a current field plus the observations. The tide dominated events were associated with a strong signal in the observations and model run with currents and negligible signal power for the model run without a current field.

An example is shown in figure 3, where a wavelet analysis was carried out for the Rustington wave buoy. Figure 3a) shows the original significant wave height (Hs) time series for the observations, the model with currents and the control model. The wavelet filter at 12 hours period is shown in 3b). Figure 3c) shows the average signal power of the 12 hour wavelet, reconstructed over a 12 hour window (3c); in this figure it can be seen at a glance where there is a large difference between the observations and the control model run. A stronger signal in the control model indicates that modulations are occurring due to other processes such as the wind at a 12 hour frequency. Where the signal power for the control model run is low, but high for the observations, this indicates that the currents have had a dominant effect on changes in the wave field at a 12 hour frequency. Comparing the wavelet 12 hour filter for the observations with the model run with currents it can be seen that the modulation amplitude 3b) and the signal power 3c) are often similar for the observations and the model. In general the current induced modulations predicted by the wave model with currents are usually in reasonable agreement with the observations at this location.

a)
b)
c)

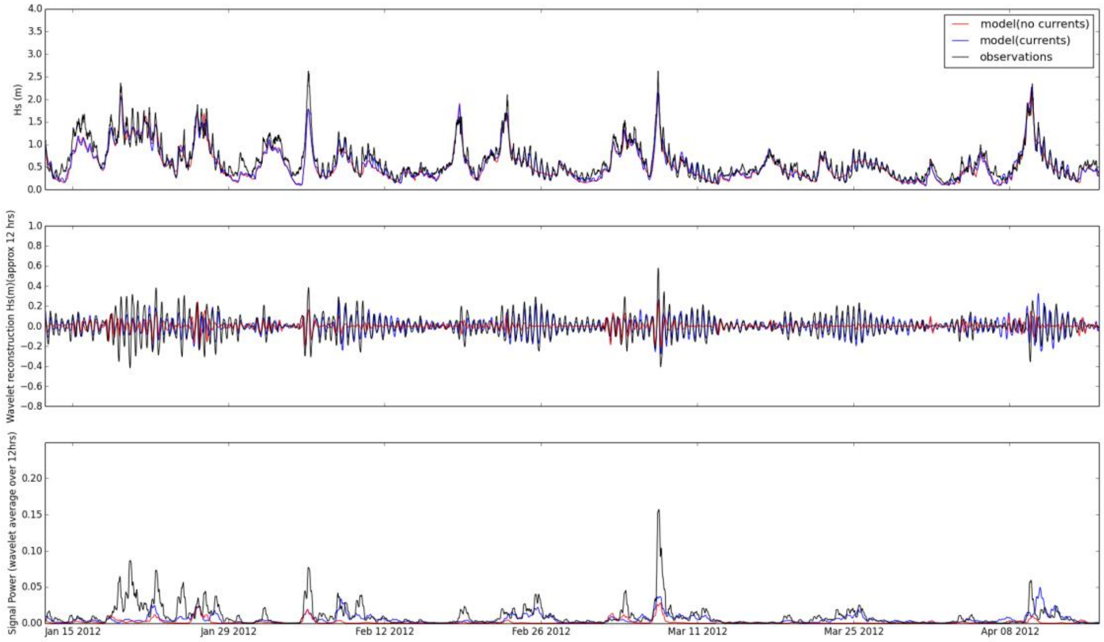

Figure 3 Example of wavelet analysis at Rustigton a) Orginal Hs b) wavelet 12 hour filter c) Signal power averged over 12 hours

5. Spatial changes in wave characteristics

Validation of the wave model against in-situ data has the limitation that this only provides information regarding the wave parameters at a single point. The output field of the model shows where the wave-current interactions have the greatest effect. Hourly difference fields from the model with currents minus the control model are useful to identify instances where the current field has significantly changed the wave model output. From these fields it is clear that in some areas the currents significantly alter both the Hs and wave period (mean zero-upcrossing period Tz, and peak period Tp), with changes clearly related to the tidal cycle in areas such as the English Channel, Irish Sea and the Bristol Channel.

The key changes in the wave field can be most readily associated with strong spatial gradients in the current field. This is well illustrated in Figure 4, which shows the effects of the current field on Hs and Tz during the ebb phase in the English Channel. In this case the currents flow in a direction (towards the west) that opposes the direction of wave propagation (towards the east) and the strongest currents (up to 2m/s) are located in a zone running across the channel between the Isle of Wight and the Cotentin peninsula. Relative to the run without currents, up-wave (to the west) of this zone Hs is increased and a corresponding decrease can be seen down-wave (to the east, figure 4d). This pattern is at odds with a concept of wave conditions being mainly controlled by local interaction with the currents, for which one might expect a maximum differential in the region of the strongest currents and similar alteration of Hs both up-wave and down-wave of this zone. Effects related to current gradients are more consistent with the observed differentials; for example wave energy up-wave of the current maxima will travel eastward faster than wave energy in the region of current maxima, leading to a build up of energy density at the leading edge of the zone with strongest currents. Conversely, where wave energy down-wave of the opposing current maxima will travel faster than in the region of current maxima, energy density will be reduced. Changes in Tz appear to be more dominated by local current values, with the reduction in Tz representing the (Doppler shift) change in frequency of the waves relative to the opposing current.

Figure 5 shows the situation three hours later, when the current has weakened and flows eastward, i.e. in the same direction as the waves. Away from the coasts, peak flow occurs in a zone running between Cherbourg and Poole Bay and the peak increase in Hs (figure 5d) is seen just down-wave of this zone, where wave propagation speeds will slow in the weaker currents. A reduction of Hs is seen close to the coasts of the Cotentin peninsula and south/east of the Isle of Wight where strong current gradients (maximum current speeds greater than 2m/s) reduce the local energy density as wave propagation speeds increase in the strongest flows. Tz values (figure 5e) are increased through the region of strongest flows, in line with a Doppler shift of frequency relative to the co-directed current.

The effects in figures 4 and 5 are, of course, not uniform with the pattern of the currents since local source term effects and refraction of wave energy across the current gradients will also occur (see section 7 for a more detailed example of this latter process). Ardhuin et al. (2012) found that current refraction has a greater impact on swell than wind-sea waves. Swell waves from the North Atlantic may propagate from west to east in the Channel, along with locally generated wind-sea, and it may be the case that current refraction effects have their strongest influence on the English Channel wave field when long period swell waves are present. Tp data in figures 4f) and 5f) show periods ranging between 6 and 12 seconds, indicating that both wind-waves and swell waves were present in the example discussed here.

Figure 6 shows an example from the Bristol Channel, where tidal range is extremely large (up to 10m) and strong currents are generated. Similar to Figure 4, this case shows ebb tide currents (with peak flows around 2.5m/s) opposing wave energy propagating from the south west. The situation appears more complex than for the English Channel case. For example Hs (figure 6d) increases in the run with currents up-wave of the current maxima region, but is reduced for much of the region of the strongest opposing currents and further down-wave. Contrary to the opposing flow case in the English Channel, Tz values are increased throughout much of the region (figure 6e), with notable exceptions in peak flow areas corresponding to the headlands south and north of Bideford Bay. Tp, in contrast, is decreased; this appears to be a similar effect to the Doppler shift of the wave period observed in the English Channel. The difference in Hs behavior may be attributable to a combination of refraction and blocking plus dissipation of high frequency waves in the region of strongest flow. The removal of high frequency wave energy would also be consistent with the increase noted in Tz. In figures 6a) and 6e) it can be seen that the largest increase in the Tz occurs where the opposing currents are fastest.

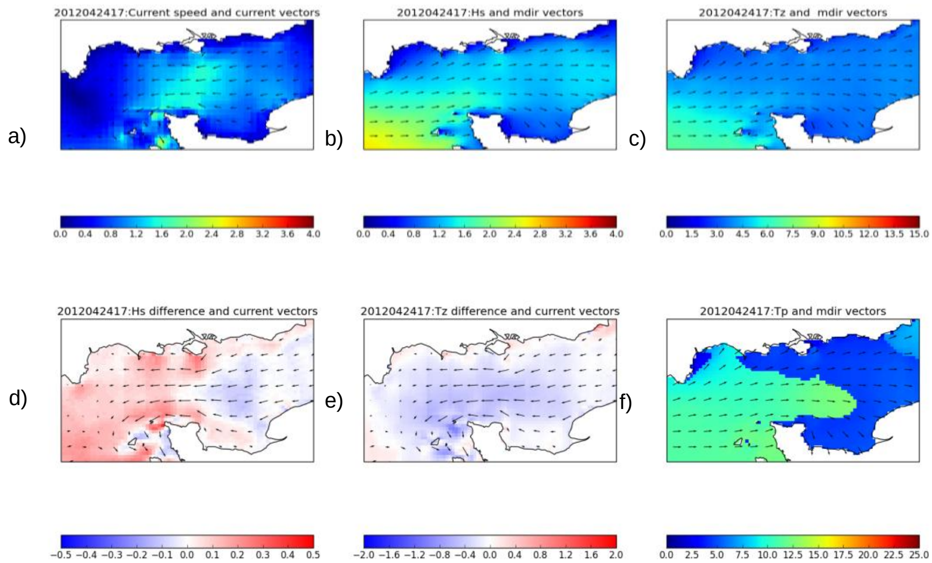

Figure 4 Output fields for the English Channel, difference plots show model with currents minus control

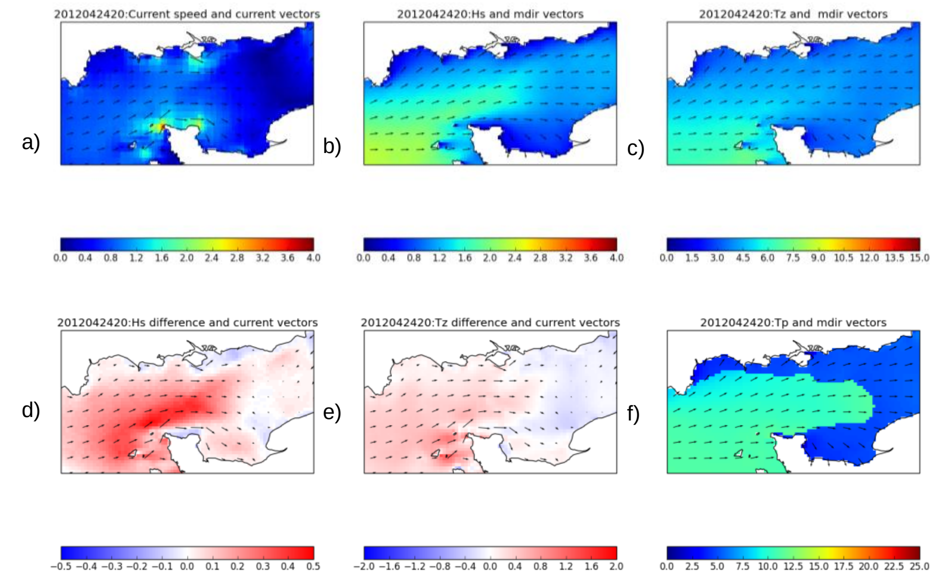

Figure 5 Output fields for the English Channel, difference plots show model with currents minus control

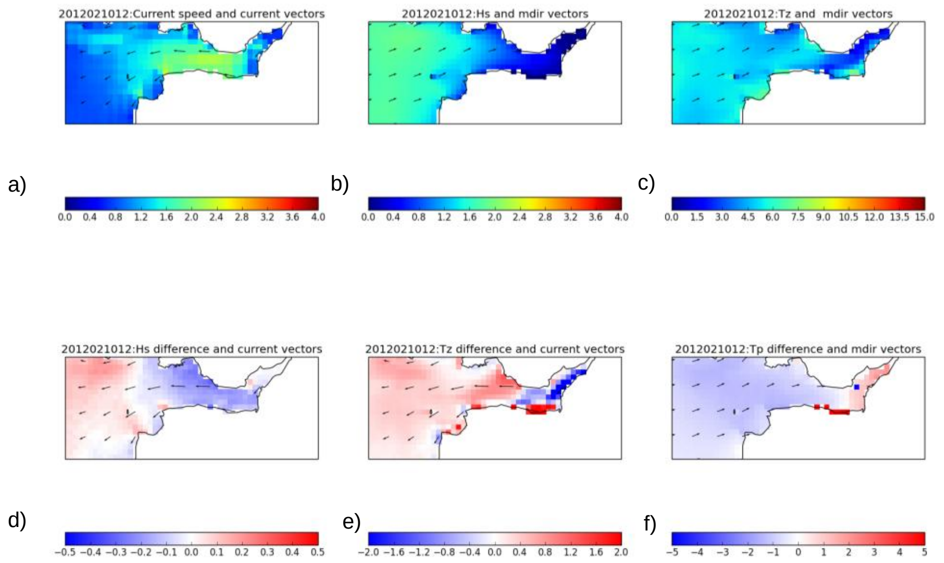

Figure 6 Output fields for Bideford, difference plots show model with currents minus control

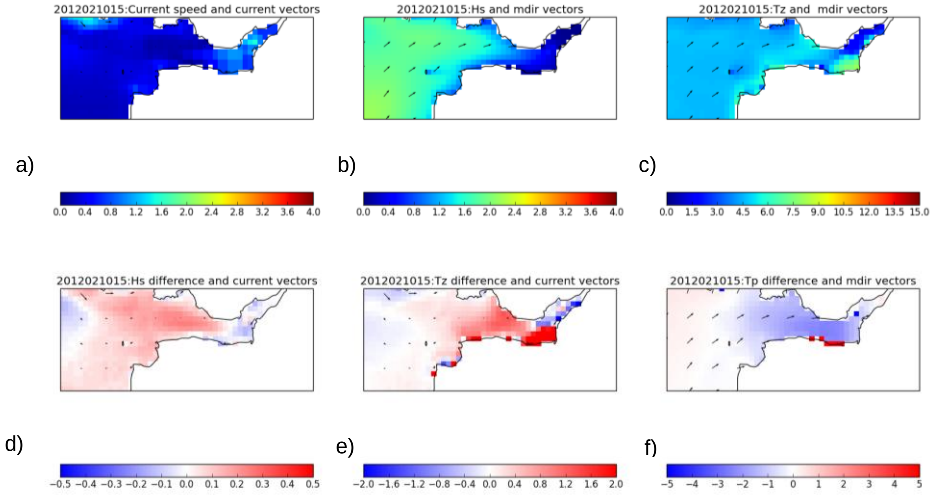

Figure 7 output fields for Bideford, difference plots show model with currents minus control

A number of further examples showing changes throughout the tidal cycle have been chosen to describe wave-current interaction in the Bristol Channel. Figure 7 shows the Bristol Channel and Bideford Bay at low tide slack water. At this point the current speeds in the region are generally low (figure 7a) and many of the differences in the wave height and wave period at this stage of the tide are attributable to up-wave effects earlier in the tidal cycle. Hs increases in the upper (eastern) reaches of the Channel (figure 7c) as the increased wave energy, generated in the western part of the Channel during the ebb phase of the tide, propagates eastward. The increase in Tz in the Bristol Channel is still present, but starts to reduce in the western approaches. Tp in the western approaches starts to increase slightly and the reduction in Tp in the upper reaches of the Channel diminishes.

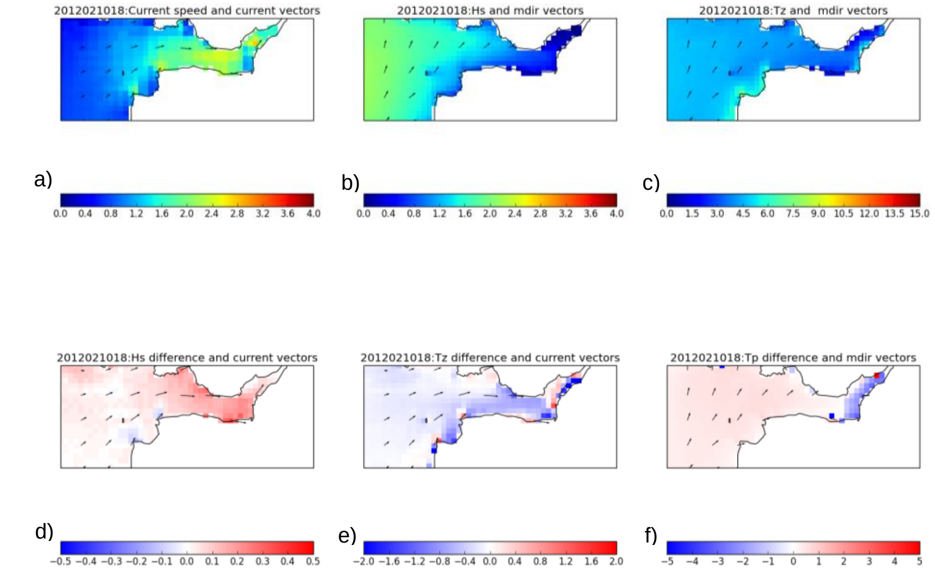

Figure 8 output fields for Bideford, difference plots show model with currents minus control

Figure 8 shows Bideford Bay and the Bristol Channel mid-flood tide. Compared to the ebb tide, the opposite change occurs in Tz and Tp. Tp is increased due to the Doppler shift caused by a following current (figure 8f). The change in wave period is not large and it should be noted that the wave direction is NW in this example, therefore the easterly current is also slightly across the mean wave direction. There is a small increase in Hs (figure 8d) in the western approaches and Hs in the upper reaches of the Channel remains elevated. The latter effect is likely to still be due to down-wave propagation of the increased Hs in the western approaches on the ebb tide. The headlands either side of Bideford Bay are an exception to the overall pattern; current speeds are also faster in this area that the rest of the Bristol Channel (figures 8a, d and e).

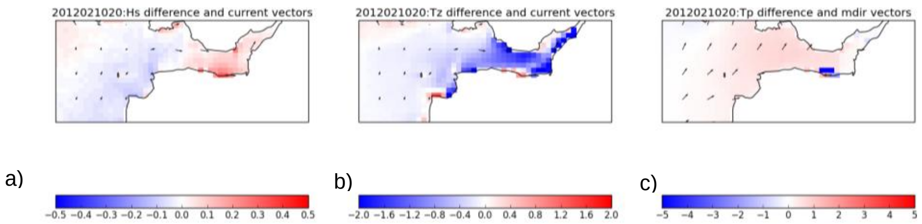

Figure 9 Output fields for Bideford, difference plots show model with currents minus control

Figure 9 shows the wave field at high tide slack water for the Bristol Channel and Bideford Bay. There is now only a small decrease in the western approaches Hs (figure 9a); this would be expected to occur where there is a slight following current. There is still some increased Hs in the upper reaches of the Bristol Channel; however it should be noted that the wave direction does not follow the current in this area, instead it is perpendicular to the current. This would diminish the reduction in energy density (and hence Hs) due to a following current and may explain this difference. There is a decrease in the Tz, which is probably attributable to the decrease in the dissipation of high frequency energy by the following current on the flood tide (figure 9b). The Tp has slightly increased, which is consistent with the dominant change in this parameter being caused by a Doppler shift (figure 9c).

To assess systematic effects of introducing the current field to the wave model, the annual mean values for Hs and Tz at each grid point in the wave field were calculated for both model hindcasts. The difference between the two models (model with currents minus control) was then plotted spatially; figures 10 and 11 show the differences in the mean for Hs and Tz respectively. In figure 10 changes are generally very small and indicate a slight decrease in mean Hs over the majority of the domain. Some small, but tangible, increases in mean Hs can be seen at a number of locations and, when this pattern is compared to the location of the fastest tidal currents over the domain (figure 12), these can be seen to generally correspond with areas of increased mean wave heights. The effect is least obvious for North Sea coast of the UK mainland. The area with strongest reduction in wave heights is the Faeroe-Shetland Channel, where strong currents are co-directed with the prevailing direction of wave propagation. In relative terms, impacts on Tz (figure 11) are even smaller than for Hs, but a pattern can be seen where less exposed coasts experience a slight increase in Tz, possibly associated with refraction effects, whilst a limited decrease in Tz occurs elsewhere in the model domain.

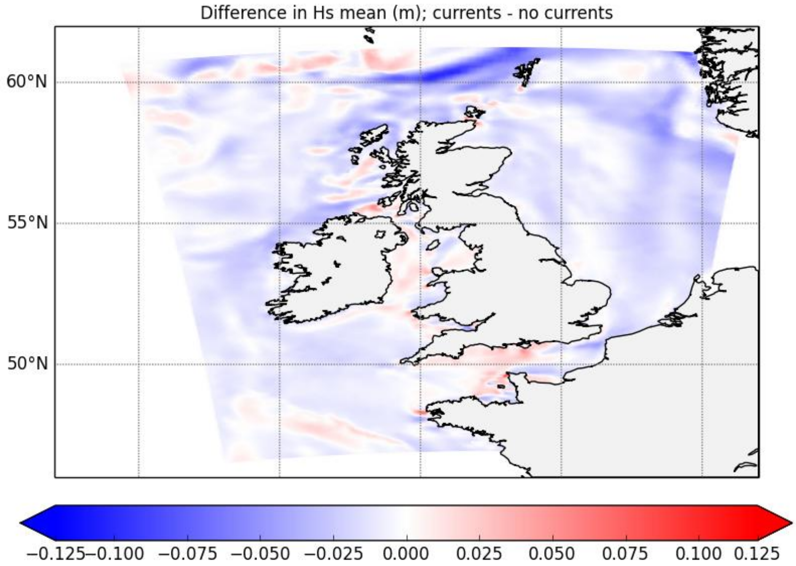

Figure 10 Hs difference in annual mean

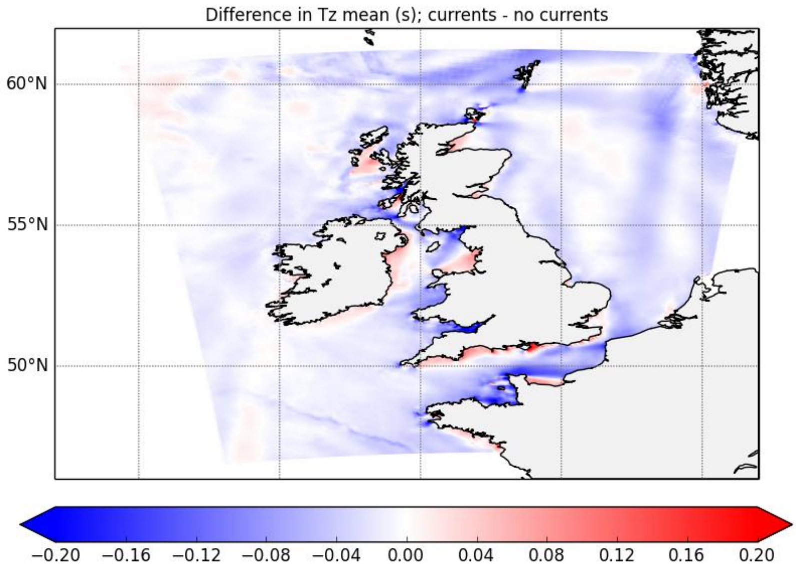

Figure 11 Tz difference in annual mean

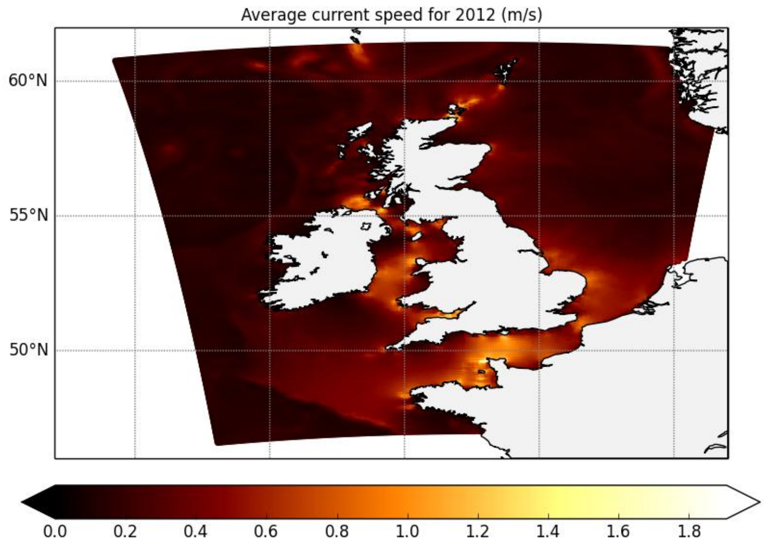

Figure 12 Annual mean current speeds (AMM7 data interpolated onto UK4 wave model grid)

Changes in the standard deviation (SD) for Hs (Figure 13) are small, reflecting the predominant influence of the wind field on wave conditions. Around the coast of the UK the most significant changes are consistent with regions known to have strong currents, for example the areas around the Bristol Channel and the Pentland Firth (between northern Scotland and the Orkney Islands). There is little change in the SD for the North Sea. Hs SD shows further variability in the Atlantic to the west of the continental shelf and, similar to mean Hs, the strong reduction in the Faeroe-Shetland Channel. The SD for Tz (Figure 14) shows a general decrease on the continental shelf and a small increase in deeper waters of the Atlantic Ocean. The exceptions to this rule are a small number of areas just downstream of headlands or locations with particularly strong current regimes; for example the coastal area around Minehead, in the Bristol Channel, and a small area to the east of the Isle of Wight. The difference in variability on and off the continental shelf probably reflects the more constrained and consistent behaviour of shallow water tides and wave fields on the continental shelf, versus the increased range of possible combinations of wave periods and directions with transient eddy structures that characterize the current field in the deep waters and more exposed fetches of the Atlantic (see Figure 14).

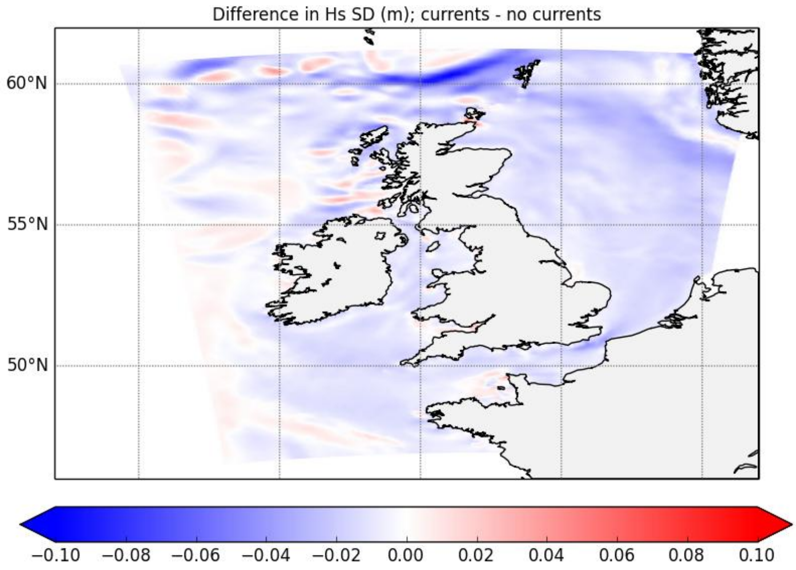

Figure 13 Hs difference in annual standard deviation

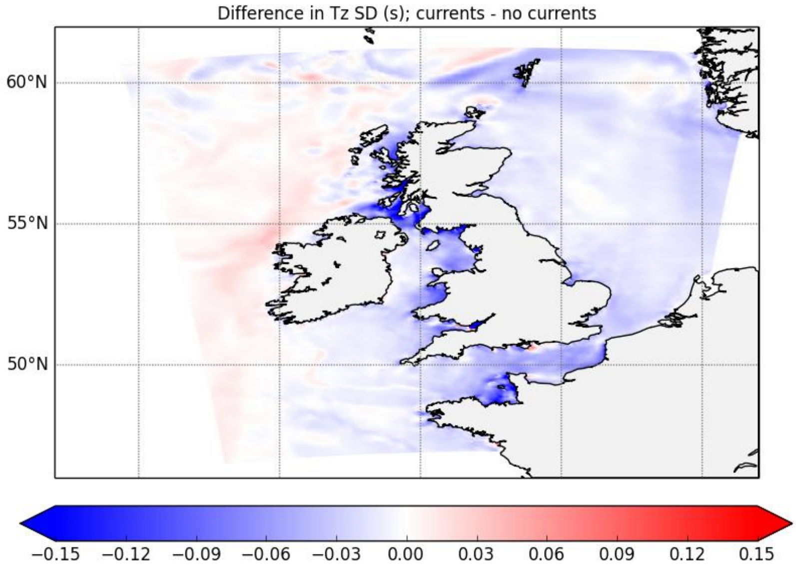

Figure 14 Tz difference in standard deviation

6. In-Situ validation in open waters

As indicated in the spatial analysis, long term changes in wave characteristics due to currents are small, particularly when compared with the background vairability due to wind forcing. This is reflected in open waters validation against in-situ observations, where changes in the root mean squared error (RMSE) and bias for the integrated parameters are small (see table 1). Locations of the JCOMM in situ observations are shown in figure 15. Overall there was no significant change in the model bias for Hs. There was a small decrease in the bias for Tp. The results for the RMSE were similar, there was a small improvement in the RMSE for Tp overall. Figure 16 shows the model error and bias across a distribution of wave heights; there is some improvement in the model bias at the largest wave heights when currents are added to the model. In general there was little difference in the overall impact of the currents for different regions (broken down as shown in figure 15). It is therefore not possible to conclude from the offshore validation results that adding a current field to the forcing of the UK4 wave model has improved the performance. It is however clear that it has not been detrimental to the model in the offshore regions.

Table 1 Model bias and RMSE from all JCOMM in-situ data (units in m or s).

	UK4		UK4-CURRENTS	
	BIAS	RMSE	BIAS	RMSE
JCOMM HS	0.00	0.32	-0.01	0.32
JCOMM TZ	-0.56	1.06	-0.57	1.07
JCOMM TP	0.26	2.46	0.16	2.38

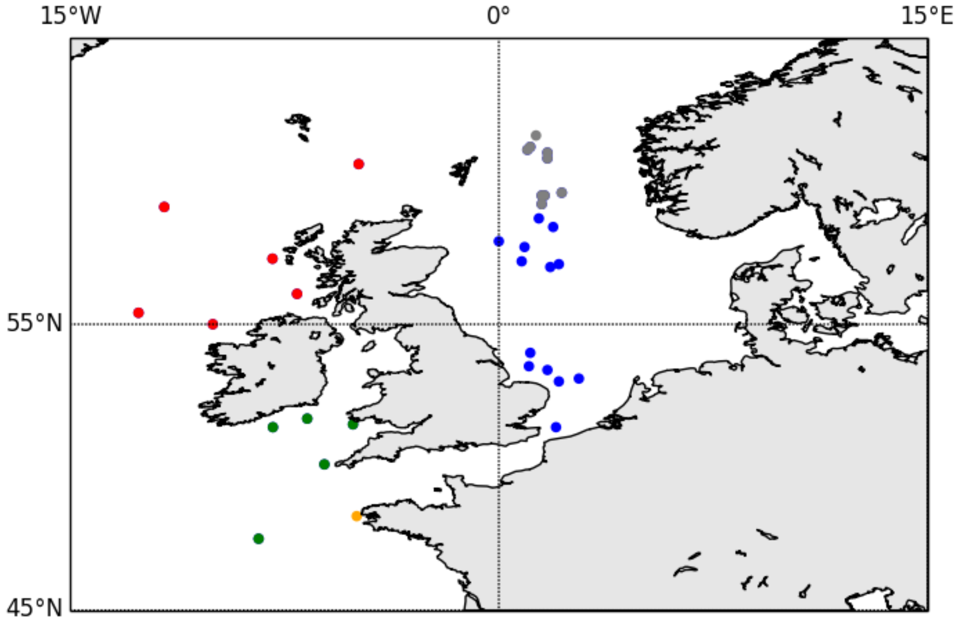

Figure 15 Map to show location of offshore JCOMM observations. Blue = North Sea (central and south) , Grey = Northern North Sea, Green = Southwest Approaches, Red = Northwest Approaches.

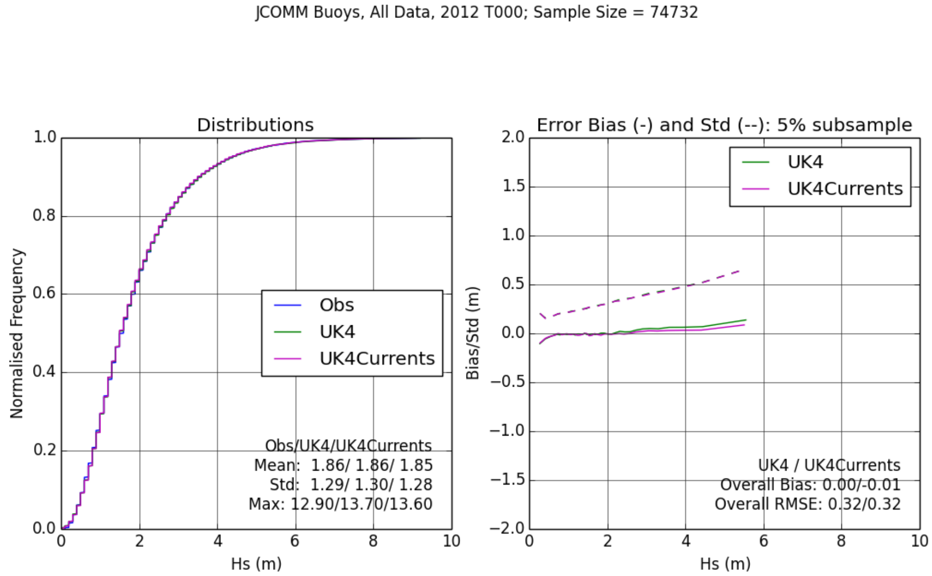

Figure 16 JCOMM comparsion, all buoys showing mean , SD, bias and mean.

7 Validation at coastal observation sites

Similar to the open waters validation, the overall change in the model bias and RMSE is small at coastal locations (see figure 17). Table 2 shows a small improvement when currents are added to the UK4 model. The overall improvement is not conclusive; however this does show that the inclusion of currents has not been detrimental to the model performance in coastal areas.

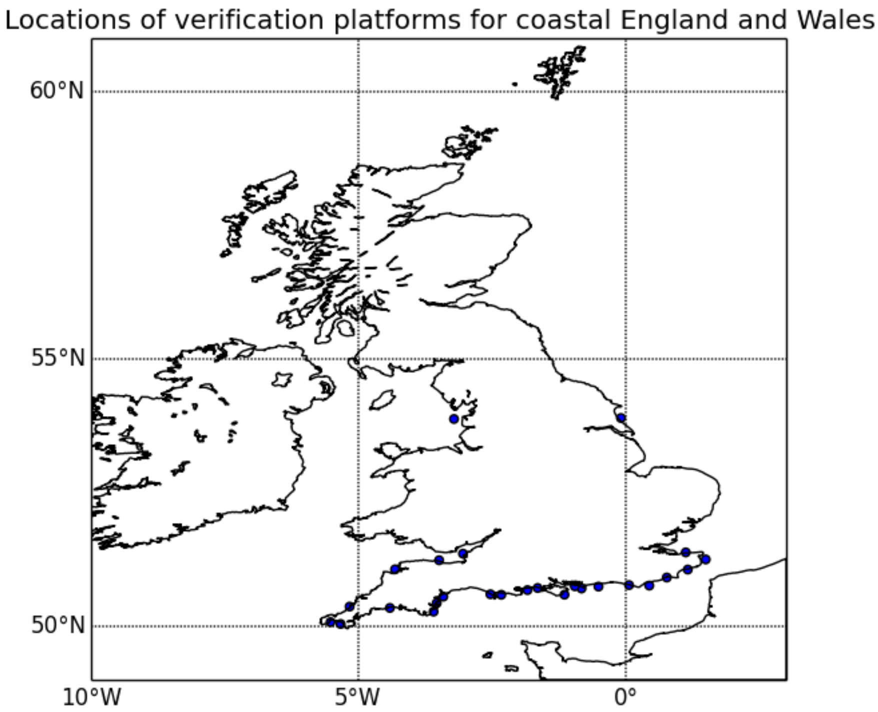

Figure 17 Map of location of coastal wave buoys.

Table 2 Bias and RMSE (m or s) for model comparison at all CCO wave buoys.

	UK4		UK4-CURRENTS	
	BIAS	RMSE	BIAS	RMSE
CCO HS	-0.03	0.26	-0.03	0.25
CCO TZ	-0.46	1.27	-0.44	1.23
CCO TP	-0.42	3.74	-0.45	3.54

Considering a breakdown by location, at the majority of buoys there is a small improvement in the RMSE for Hs, which appears related to a similar improvement in the model bias (see Table 3). This indicates that the model successfully represents both systematic (long term) and high frequency changes in Hs and Tz due to interaction of the waves with currents. An example of these fluctuations is at Rustington, shown in figure 18. In many cases an increase in the observed peak Hs can be seen during each tidal cycle. This is also represented in the wave model once a current field has been added. Adding the effect of the currents to the wave model has the effect of reducing a small negative bias at this site of -0.06 to -0.04. The RMSE was reduced from 0.22m to 0.19m. This is not a large improvement, however at many locations the RMSE is around 0.2m so this is an improvement of about 10%.

Table 3 Hs Bias and RMSE (m) at individual CCO wave buoys

	UK4		UK4-Currents	
	Bias	RMSE	Bias	RMSE
Bideford	-0.04	0.24	-0.04	0.24
Chesil	-0.09	0.21	-0.07	0.19
Cleveleys	-0.14	0.21	-0.13	0.2
Folkestone	-0.12	0.21	-0.11	0.2
Milford	-0.06	0.17	-0.05	0.15
Minehead	-0.33	0.4	-0.29	0.36
Penzance	0.13	0.21	0.12	0.19
Rustington	-0.06	0.22	-0.04	0.19
Sandown	0.22	0.33	0.25	0.35
Weston	0.07	0.22	0.03	0.21

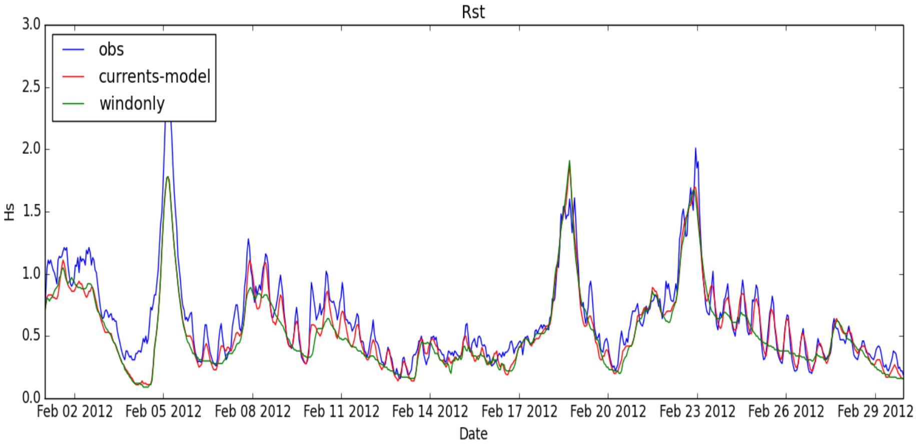

Figure 18 Hs time-series for Rustington

At many individual CCO wave buoy locations there has been some improvement in the model RMSE for Tz when currents are added (see table 4). However, the percentage error for the RMSE against background mean Tz is relatively high at 30%. At Minehead , where strong tidal currents are observed (observed mean Tz 4.01(s)) the RMSE is 47% in the control model and is reduced to 39% with addition of currents. In most cases however the change in bias and RMSE is small. Tp bias and RMSE were generally improved when currents were added to the model (table 5). The mean observed Tp at all the CCO wave buoys was 7.24 seconds, therefore the relative error is generally large for this parameter at many locations.

Table 4 Tz Bias and RMSE (S) at individual CCO wave buoys.

	UK4		UK4-CURRENTS	
	BIAS	RMSE	BIAS	RMSE
BIDEFORD	-0.17	1.09	0.23	1.04
CHESIL	-0.85	1.33	-0.79	1.24
CLEVELEYS	-0.59	0.77	-0.51	0.68
FOLKESTONE	-0.91	1.14	-0.81	1.03
LOOE	-0.66	1.11	-0.64	1.06
MILFORD	-0.73	1.30	-0.68	1.15
MINEHEAD	-1.43	1.89	-0.88	1.56
PENZANCE	-0.46	1.22	-0.44	1.23
RUSTINGTON	-0.23	0.79	-0.23	0.71
WESTON	1.13	2.12	0.73	1.81

With regard to the verification of wave periods, it is worth noting that the Doppler equation, (equation 1) relates the absolute period to the relative (intrinsic) period. The wave model outputs the relative period, which is the period of the wave in a moving frame of reference with the current (this output is appropriate as the relative wave periods allow a correct evaluation of wave steepness). However, the wave buoys measure the period from a fixed location, i.e. the absolute wave period. If the Doppler equation is considered for a 10 second wave in deep water moving in the same direction as a 2m/s current, the difference in period between the relative and absolute period is approximately 1.1 seconds. This example is a very simple case using the higher range of current speeds that are observed at coastal locations around the UK, but indicates that there could be a significant difference between the period that is output by the wave model and what is measured by the wave buoy. It might therefore be anticipated that the addition of currents to the wave model would cause degradation in the RMSE for wave period. This is not the case; indeed, at most locations, a small improvement in the model prediction of Tz and Tp is observed. The reason for this is likely to be that other processes, such as refraction and changes in the wave frequency due to energy density changes in current gradients, have a greater effect on the wave period at coastal locations than the Doppler shift. The absolute period from the model can be obtained using the Doppler equation, comparison of this with the wave buoy data may result in an improved in the validation for this parameter.

Table 5 Tp Bias and RMSE (S) at individual CCO wave buoys.

	UK4		UK4-Currents	
	Bias	RMSE	Bias	RMSE
Bideford	0.22	2.42	0.09	2.39
Chesil	-0.57	3.11	-0.77	2.90
Cleveleys	-0.34	2.45	-0.30	1.95
Folkestone	-0.99	2.63	-0.87	2.40
Looe	-0.33	4.57	-0.65	4.36
Milford	-1.34	3.92	-1.36	3.73
Minehead	-1.03	3.90	0.12	3.51
Penzance	-0.08	4.33	-0.28	4.12
Rustington	-0.05	3.16	-0.16	2.94
Weston	4.13	6.04	3.54	5.80

8. Wavelet analysis for wave model validation

8.1 Cross correlation between wave and the tidal signal.

For a selection of coastal sites, reconstructed high pass wavelet signals for Hs and Tz at the 12 hour frequency were compared with the tidal modulations in sea surface height at each wave buoy site for a 2 month period, from 2012/01/02 to 2012/04/01. A lagged cross correlation analysis was used to determine the maximum Pearson Correlation between the signals and the time difference at which this occurred. The results are shown in table 6 for (respectively) observations, model with currents and the control run without currents. In the observed data, relatively strong cross correlations between Hs/Tz and sea surface height were found at Rustington and Bideford Bay; moderate correlations were found at Chesil and Pevensey Bay; whilst Looe Bay showed no correlation for Hs and a moderate correlation for Tz.

At Rustington the observed modulations in Hs and Tz both correlate strongly with the sea surface height; phase of the peak correlation indicates that the maxima in Hs and Tz occurred at high tide with the minimum values at low tide. Cross correlation values for Hs and Tz from the model run with currents are similar to those of the observations. The observation peak correlation is also in phase with the model with currents. In contrast, the control run shows no correlation with the sea surface height. This is a strong indication that the addition of a current field improves the performance of the model. Since tidal elevations are not included in the wave model, the results also indicate that the effects on the wave field due to wave-current interactions are predominantly responsible for the tidal signal observed at Rustington.

Table 6 Maximum Pearson Correlation Coefficient between the sea surface height and the wavelet anaylsis (using a wavelet period of 12 hours).

Location	Wave parameter	Pearson Correlation Coefficient (Obs, Model, Model – no currents)	Lag behind SSH (Obs, Model, Model – no currents)
Rustington	**Hs**	**0.637, 0.623 , 0.005**	**12, 12 , 12**
	Tz	**0.645, 0.559 , 0.113**	**0, 0, 4**
Bideford	**Hs**	**0.706, 0.501 , 0.014**	**8, 9 ,10**
	Tz	**0.666, 0.266, 0.146**	**6, 5, 1**
Looe Bay	**Hs**	**0.066, 0.060 , 0.024**	**5, 9, 6**
	Tz	**0.389, 0.256, 0.109**	**5, 2, 4**
Pevensey	**Hs**	**0.373, 0.341, 0.062**	**0, 0, 5**
	Tz	**0.449, 0.514, 0.101**	**1, 0, 4**
Chesil	**Hs**	**0.519, 0.170, 0.098**	**3, 3, 4**
	Tz	**0.580, 0.188, 0.056**	**3, 6, 9**

At other locations in the English Channel, to the east and west of the Isle of Wight, the correlation between the wave parameter modulations and the sea surface height is lower than at Rustington. Current speeds, which are often in excess of 2m/s in the central Channel near the Isle of Wight (see figure 19), reduce to the east and west. There is also a lag between the modulations and the sea surface height that increases to the west of Rustington. In general the tidal signal in the wave field is weaker at the other channel locations than at Rustington. This is evident in the correlation values between the sea surface height and the wavelet 12 hour filter for the observations. This weakening in the tidal signal is reflected in the model with currents at Pevensey (eastern Channel) and Looe (western Channel).

The exception to this is at Chesil where the correlation is notably higher for the observations. The tidal range at Chesil has a maximum of about 4m, which is similar to Rustington; however, the bathymetry around or approaching Chesil may result in some wave focusing occurring with changes in the water depth, which is not accounted for in the wave model at this location. There are also some areas of faster currents near the Chesil buoy that may not be well resolved by the AMM7 model. These statements are speculative however and should be investigated further when water levels are added to the model.

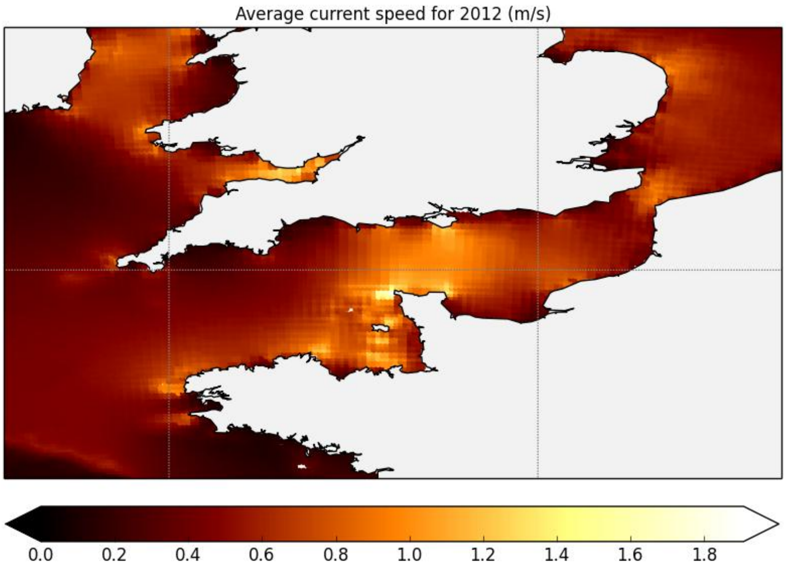

Figure 19 Average current speeds for 2012 for the south of the UK (m/s)

At Bideford, in the Bristol Channel, the strong cross correlation between the wave parameter modulations and the sea surface height modulations is also greater for the observations than for the wave model. Again, this indicates that the model is not able to fully represent the effect of the tide at this location. Nevertheless, the magnitude and phase of peak correlation for the model with currents is significantly closer to the observed value than for the run without currents, implying that the addition of a current field has had a positive impact on the model performance. The significant lag that exists between the wave parameter modulations and the sea surface height suggests that the dominant processes at this location may be different from those in the area surrounding the Isle of Wight. The tidal range is large at Bideford (approx 8m), again suggesting that the absence of water level changes in the model is likely to be the reason for this.

8.2 Case Studies

8.2.1 Rustington: 6th -13th February 2012

Signal power series derived from the wavelet analysis identified a number of time periods where the currents had a dominant impact on the wave field. This case study approach allowed the local wave-current processes to be investigated in more detail.

a)

b)

c)

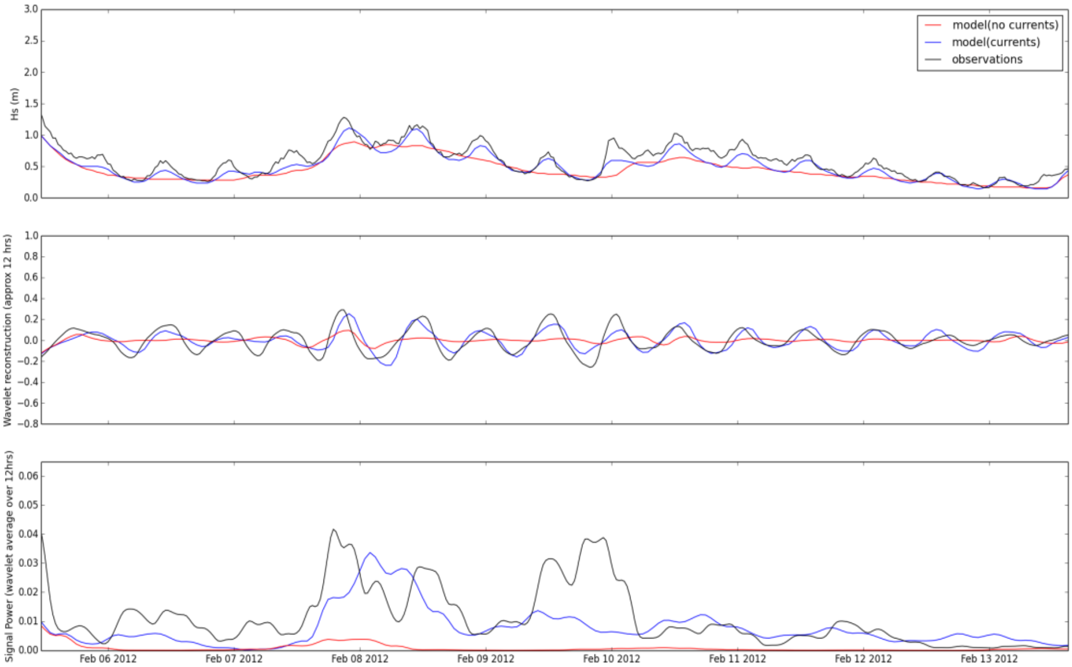

Figure 20 a) Hs time series at Rustington b) Wavelet reconstruction for an approximately 12 hour period c) The signal power of the reconstruction averaged over a 12 hour window

A case study where currents had a particularly strong impact was identified from the records at Rustington for the period of the 6th to the 13th February 2012. The Hs time series for the observations, model with currents and the control run is shown in figure 20, along with the 12hour wavelet reconstruction (figure 20b). The main wave parameters during this time period are shown in figure 21. The difference in the signal power between the model with currents and the control run is evident. Hs and Tz (figure 21a and b) show strong modulations; these are approximately in phase with the sea surface height for the model with currents and the observations, which are absent in the control run. There are also significant modulations in the directional spread (figure 21c).

The peak period (Tp) and peak wave direction record for the wave buoy at Rustington (figure 21d), shows regular large fluctuations. The sharp increase in Tp, along with the change in direction of over 100º, is due to a bimodal wave spectrum comprising two different sources of wave energy. One component comprises swell waves, propagating toward the northeast from the Atlantic, whilst the other comprises locally wind generated waves from an easterly direction (propagating westward). The presence of a bimodal sea means that, in order to better understand the processes causing variations in the wave parameters, it is necessary to look at the wave spectrum. The sudden large changes in the Tp for the total spectrum indicate that peak energy in the spectrum is switching periodically from the wind-sea to the swell.

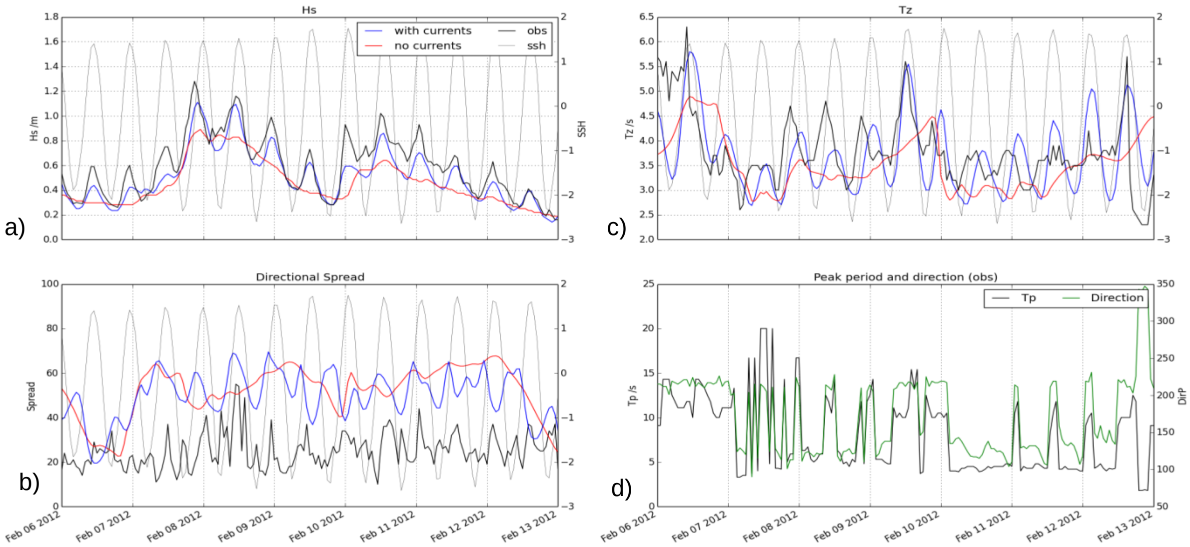

Figure 21 Time series at Rustington for Observations and Models. a) Hs b) Tz c) Directional spread d) Tp

The frequency spectrum from the wave buoy confirms that the fluctuations in Tp are being caused by periodic increases in swell wave energy (figure 22a) and b). It was found that there was a significant increase in swell wave energy at the high tide, while the wind-sea energy had relatively little change. It is this increase in the swell energy, rather than a reduction in the wind-sea, that causes the shift in Tp seen in figure 21d.

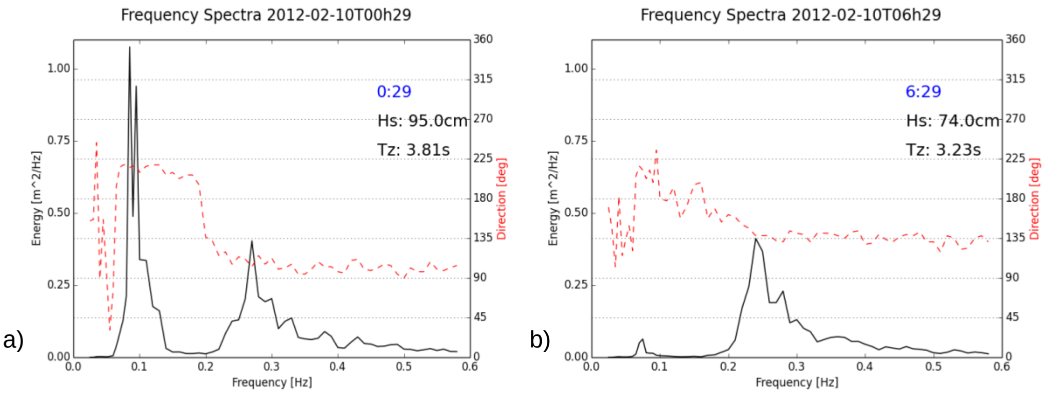

Figure 22 a) Frequency Spectrum at Rustington at high tide b) low tide.

The model spectra for the same time period show a similar increase in swell energy at high tide (figure 23). The directional wave spectra from the model also indicate that this increase in energy is related to an increase in the directional spread. This suggests that a change in the direction of propagation of swell waves (due to current refraction) further offshore leads to more energy being incident to the coastal zone near Rustington. The model without currents does not show this change in the swell part of the wave spectrum (figure 23b.) The wave spectrum at low tide for the control model is shown in figure 24a) and the spectrum for the model with currents in figure 24b). If these are compared with figure 23 a) and b) it can be seen that there is little change in the swell over the 6 hour period for the control model. For the model with currents however, there is a reduction in swell energy and a change in the directional spread. The wave field for the model with currents also shows refraction of the swell by currents during the tidal cycle. A following current (rising tide) refracts swell waves towards the coast at Rustington, increasing the swell energy and directional spread. There is a gradient in current speed from the coast to the deeper water so that, in a following current, the waves in the deeper water are travelling faster than those closer to the coast. This leads to refraction towards the coast. In an opposing current (ebbing tide) the waves in the deeper water, where current speeds are faster, travel slower. This causes wave energy to be refracted away from the coast so that the swell energy incident at Rustington diminishes. The refraction of swell energy towards Rustington peaks at or near high tide.

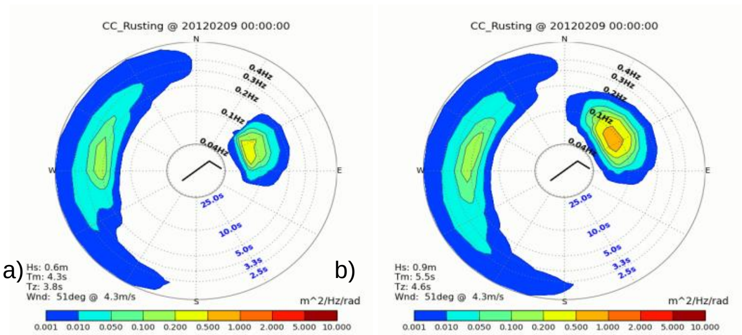

Figure 23 Directional wave spectrum at Rustington at high tide a) Model without currents b) Model with currents

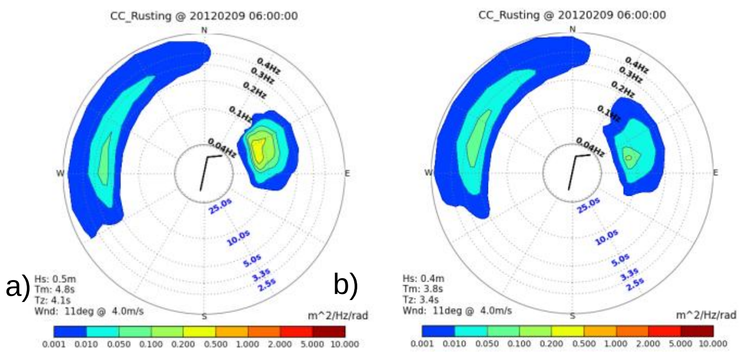

Figure 24 Directional wave spectrum at Rustington at low tide a) Model without currents b) Model with currents

During the time period of this case study the RMSE was calculated at Rustington for both model runs. When currents were added to the model there was a decrease in the RMSE from 0.18m to 0.15m. This is a significant improvement in the relative error at this location.

8.2.2 Bideford: 21st-22nd March 2012

The wavelet analysis identified a similar case study at Bideford for 21st-22nd of March 2012. At Bideford the signal power in the 12hr wavelet is significantly greater for the observations than for the wave model with a current field (see figure 25). There is only a small difference between the control run and the model run with a current field (figure 26). This suggests that the modulations in the wave parameters observed at the wave buoy are caused by additional processes to changes in current speed and direction. The changes in water depth due to the tide have not yet been added to the wave model. Therefore changes in depth related dissipation and refraction are not accounted for. The maximum tidal range during the period of this case study is just over 8m at Bideford; almost double the range at Rustington. The observed wave parameters for Bideford are shown in figure 27. Figure 27d) shows that the observed Tp varied between 10 and 12.5 seconds during the time period. This, along with low wind speeds (figure 27e), is an indication that the sea state was swell dominated during this case study.

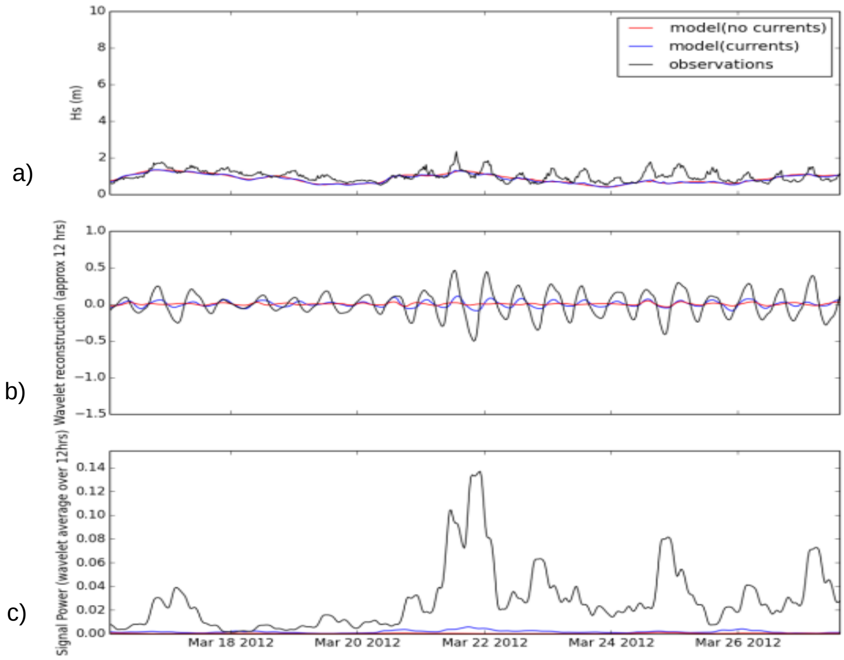

Figure 25 a) Hs time series at Bideford b) Wavelet reconstruction for an approximately 12 hour period c) The signal power of the reconstruction averaged over a 12 hour window

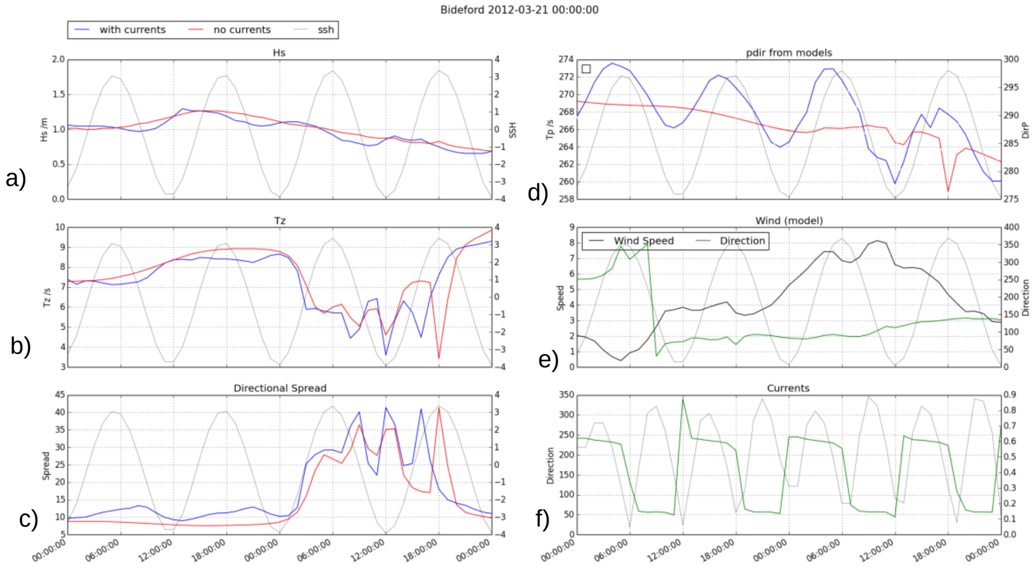

Figure 26 Time series of model with currents and model without currents a) Hs b) Tz c) Directional Spread d) Tp and peak direction e) wind speed and direction f) current speed and direction

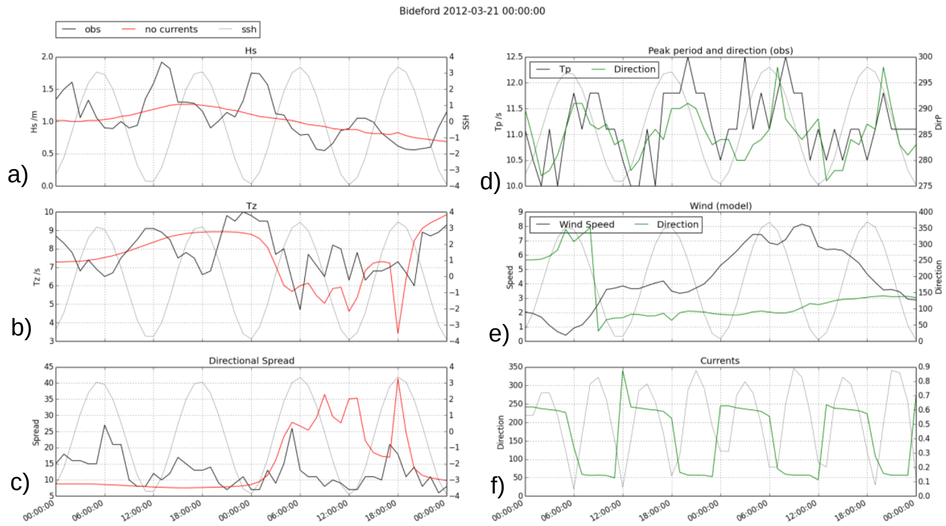

Figure 27 Time series of observations and model without currents a) Hs b) Tz c) Directional Spread d) Tp and peak direction e) wind speed and direction f) current speed and direction.

9. Conclusions

This study has tested the performance impacts of forcing the Met Office (4km resolution) wave model for UK waters with (7km resolved) current fields in addition to wind fields. The overall effect of adding currents to the wave model is to improve the model performance in coastal areas where tidal processes are important. UK-wide, long term, improvements in model validation are negligible; however the model performance has not been degraded. Systematic spatial changes in the wave field over a 1 year hindcast reflect where the strongest tidal currents occur.

At high temporal frequency (hours), the addition of currents leads to significant changes in model wave fields. Wave energy density is most strongly modified in regions with strong current gradients, where wave energy propagation speeds and refraction are affected in addition to local modifications wave generation and dissipation (via the model source terms). In open waters, wave periods are predominantly affected by local currents modifying the (current-) relative wave frequencies output by the WAVEWATCH III.

In offshore locations the application of currents has made negligible difference to the RMSE and bias of the model for a one year validation period (2012). Small improvements were noted in some regions, where bias was reduced for larger wave heights. However, the difference between models with and without currents is not conclusive in most offshore regions. In coastal areas, long term validation using the CCO wave buoys shows some improvements, but not at all locations. The largest improvements were found at locations with strong currents, where the model with currents had errors that were 10% lower for both Hs and periods Tp and Tz.

Over a large area and period of time, limited impacts are to be expected, since the primary cause of errors in the wave model will be associated with growth and dissipation of wind-sea. This is mainly impacted by errors in the atmospheric forcing field. Therefore a case study approach was applied, using wavelet analysis to identify locations and time periods where the tide has a dominant effect on the wave field. In a number of cases a significant improvement in the wave model performance has been identified, for example at Rustington. Case studies at other locations, such as Bideford, suggest that tidal effects other than currents contribute more significantly to changes in the wave field over the tidal cycle. It is likely that the model may need to include variations in water levels in order to more fully capture the effects of the tide.

Overall, these trials indicate that adding the current field to the wave model would make a positive impact to short range forecast performance around the UK coastline. The UK4 wave model with additional current forcing was therefore implemented in the Met Office operational suite at OS37, in March 2016.

10. References

Ardhuin, Fabrice, Aron Roland, Franck Dumas, Anne-Claire Bennis, Alexei Sentchev, Philippe Forget, Judith Wolf, Françoise Girard, Pedro Osuna, and Michel Benoit. "Numerical wave modeling in conditions with strong currents: Dissipation, refraction, and relative wind." Journal of Physical Oceanography 42, no. 12 (2012): 2101-2120.

Bidlot, J.R., Li, J.G., Wittmann, P., Fauchon, M., Chen, H., Lefevre, J.M., Bruns, T., Greenslade, D., Ardhuin, F., Kohno, N. and Park, S., 2007, November. Inter-comparison of operational wave forecasting systems. In Proceedings, 10th Int. WOrkshop of Wave Hindcasting and Forecasting, Hawaii.

Bidlot, J.-R., 2012: Present status of wave forecasting at E.C.W.M.F. In Proc. ECMWF Workshop on Ocean Waves, Reading, 2012, p1-15.

Daubechies, Ingrid. "The wavelet transform, time-frequency localization and signal analysis." Information Theory, IEEE Transactions on 36.5 (1990): 961-1005.

Davies, T., Cullen, M.J.P., Malcolm, A.J., Mawson, M.H., Staniforth, A., White, A.A. and Wood, N., 2005. A new dynamical core for the Met Office’s global and regional modelling of the atmosphere. Q.J.R. Meteorol. Soc., 131, p.1759–1782.

Dodet, Guillaume, Xavier Bertin, Nicolas Bruneau, André B. Fortunato, Alphonse Nahon, and Aron Roland. "Wave-current interactions in a wave-dominated tidal inlet." Journal of Geophysical Research: Oceans 118, no. 3 (2013): 1587-1605.

Flather, R. A.: A tidal model of the northwest European continental shelf, Memoires de la Societe Royale de Sciences de Liege, 6, 141–164, 1976.

Hayes, John G. "Ocean current wave interaction study." Journal of Geophysical Research: Oceans (1978–2012) 85.C9 (1980): 5025-5031.

Holthuijsen, L. H., and H. L. Tolman. "Effects of the Gulf Stream on ocean waves." Journal of Geophysical Research 96.C7 (1991): 12-755.

Holthuijsen, Leo H. Waves in oceanic and coastal waters. Cambridge University Press, 2007.

Janssen, Peter AEM. "Quasi-linear theory of wind-wave generation applied to wave forecasting." Journal of Physical Oceanography 21.11 (1991): 1631-1642.

Kunze, Eric. "Near-inertial wave propagation in geostrophic shear." Journal of Physical Oceanography 15.5 (1985): 544-565.

Li, Jian-Guo. "Upstream non-oscillatory advection schemes." Monthly Weather Review 136.12 (2008): 4709-4729.

Longuet-Higgins, Michael S., and R.W. Stewart. "Changes in the form of short gravity waves on long waves and tidal currents." Journal of Fluid Mechanics 8.04 (1960): 565-583.

Longuet-Higgins, Michael S., and R. W. Stewart. "Radiation stresses in water waves; a physical discussion, with applications." Deep Sea Research and Oceanographic Abstracts. Vol. 11. No. 4. Elsevier, 1964.

Madec, G.: NEMO ocean engine. Note du Pole de modélisation, Institut Pierre-Simon Laplace (IPSL), France, 27, 1288-1619, 2008.

O'Dea, E. J., A. K. Arnold, K. P. Edwards, R. Furner, P. Hyder, M. J. Martin, J. R. Siddorn et al. "An operational ocean forecast system incorporating NEMO and SST data assimilation for the tidally driven European North-West shelf." Journal of Operational Oceanography 5, no. 1 (2012): 3-17

Palmer T., Stratton, T., Saulter, A. and Henely, E., 2015 Case study comparisons of UK macro-tidal regime wave and current interaction processes; mesoscale wave model versus coastal buoy data.

Saulter, A., 2015: Assessment of WAM Cycle-4 based source terms for the Met Office global-regional wave modelling system. Forecasting Research Technical Report No 598, 2015.

Schumann, E. H., High waves in the Agulhas current, The South African Shipping News and Fishing Industry Review, 25–27, 1975.

Schumann, E. H., High waves in the Agulhas current, Mariners Weather Log, 20, 1976.

Tolman, Hendrik L. "The influence of unsteady depths and currents of tides on wind-wave propagation in shelf seas." Journal of Physical Oceanography 20.8 (1990): 1166-1174.

Tolman, Hendrik L. "A third-generation model for wind waves on slowly varying, unsteady, and inhomogeneous depths and currents." Journal of Physical Oceanography 21.6 (1991): 782-797.

Tolman, Hendrik L. "User manual and system documentation of WAVEWATCH III TM version 3.14." Technical note, MMAB Contribution 276 (2009).

Tolman, H. L. "the WAVEWATCH III® Development Group (2014), User manual and system documentation of WAVEWATCH III® version 4.18." Tech. Note 316, NOAA/NWS/NCEP/MMAB.

Torrence, Christopher, and Gilbert P. Compo. "A practical guide to wavelet analysis." Bulletin of the American Meteorological society 79.1 (1998): 61-78.

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