MODELLING WAVE-TIDE INTERACTIONS AT A WAVE FARM IN THE SOUTHWEST OF ENGLAND

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The Wave Hub project will create the world's largest wave farm off the coast of Cornwall, Southwest England. This study is to investigate wave and tide interactions, in particular their effects on bottom friction and sediment transport at the wave-farm coast. This is an ambitious project research which includes the use of a very complex numerical modelling system. The main question to answer is how waves, tidal currents and winds affect the bottom friction at the Wave Hub site and the near-shore zone, as well as their impact on the sediment transport. Results show that tidal elevation and tidal currents have a significant effect on the wave height predictions; tidal forcing and wind waves have a significant effect on the bed shear-stress, relevant to sediment transport; waves via radiation stresses have an important effect on the long-shore and cross-shore velocity components, particularly during the spring tides. Waves can impact on bottom boundary layer and the mixing in the water column. Interactions between waves and tides at the Wave Hub site is important when modelling coastal morphology influenced by wave energy devices. This open-source modelling system tool will help the study of physical impacts on the Wave Hub farm area.

Keywords: Wave Hub; marine renewable energy; wave-current interaction; wave-tide interaction; SWAN; ROMS.

INTRODUCTION

The Wave Hub project aims to create the world's largest wave farm for demonstration and proving of operation of arrays of wave energy converter devices, located at the southwest coast of England (Figure 1). Recent studies at the Wave Hub site suggest that wave induced currents are important in controlling sediment movement (SWRDA, 2006). Better understanding of tidal effects on waves and sand transport is crucial to wave resource characterization and environmental impact assessment of the wave farm at the Wave Hub site.

A modelling study done by SWRDA (2006) suggests that the wave energy converters (WECs) installed at Wave Hub would cause a reduction between 3% - 5% of wave height on the coast off to the Wave Hub site, as well as changes in surface tidal currents and offshore bed elevations. Key areas of study are the estimated wave height attenuation and tidal currents in the lee of the Wave Hub site and the associated impact on sedimentation, beach topography and beach state. From the perspective of the effect on the coast, the tidal control on sand transport is weak and regionally uncertain, and volumes of sand involved are limited in comparison with other sectors of the English coast. Wave induced currents are more important in controlling sediment movement. The prevailing winds are from the south and west, but easterly winds can produce significant movement of sediment. Storm events cause movement of sand on the inner shelf but the effects are greater in the narrow, shallower near-shore zone. Also cross-shore sediment transport takes place. (Buscombe & Scott, 2008).

Millar et al (2006) carried out a study at the Wave Hub site with to estimate the impacts of WECs on the near-shore wave climate by analysing the wave energy transmitted to the devices and to the shoreline. They applied the SWAN model and used field observations from wave buoys. They concluded that at 90% transmission the average reduction in significant wave height was of the order of 1cm, and that the stretch of the coast most likely to be affected was between Godrevy and Towan Heads. The admiralty pilot reports tidal streams on the north coast of Cornwall at a spring rate of 1 to 2 knots (0.5 to 1.0 m/s). In the modelling study published by SWRDA (2006), the deployed buoy recorded wave parameters and tidal currents, maximum velocities of 1.2 m/s were measured, the hydrodynamic model applied (Flow3D) was forced by four tidal constituents during a storm to assess the impact of the deployed devices on tidal currents, sediment regime and wave buoy data from 03/02 to 14/02 2005 was used in the calibration of the model. The devices used for worst case scenarios in the simulation were the wave dragons. The sediment transport was modelled with and without the presence of wave and current regime, results of the sediment transport for the worst case scenario shows significant changes at the Wave Hub site.

The aim of this study is to investigate wave-tide interactions, in particular their effects on sediment transport at the wave-farm coast, looking at the vertical column stratification through the relationships of wave-currents and bottom stresses. This project includes the use of a very complex numerical modelling

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system. The main question to answer is how waves, tidal currents and winds affect the bottom friction at the Wave Hub site and the near-shore zone, as well as their impact on the sediment transport.

THE WAVE-CURRENT MODELLING SYSTEM

The SWAN model

The Simulating WAves in the Near-shore (SWAN) wave model is a phase averaged wind wave model developed by Booij et al. (1999) that is widely used to simulate wave conditions in coastal areas, where propagation, wave generation and dissipation processes are represented as: refraction and shoaling, reflection, diffraction, bottom friction, and depth induced breaking. The model solves the action balance equation, where action density is $N(\sigma,\theta)$, which is the energy density $E(\sigma,\theta)/\sigma$. The relative wave frequency σ is related to the fixed wave frequency ω by the wave number vector $\boldsymbol{k}$ and mean current vector $\boldsymbol{u}$.

$$\sigma = \omega - \boldsymbol{k} \cdot \boldsymbol{u} \tag{1}$$

The evolution of the wave field in SWAN is described by the action balance equation

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}(c_x + u)N + \frac{\partial}{\partial y}\left(c_y + v\right)N + \frac{\partial}{\partial \sigma}c_\sigma N + \frac{\partial}{\partial \theta}c_\theta N = \frac{S_{tot}}{\sigma} \tag{2}$$

which describes the local rate of change of action density with time, t, and the propagation of action density in each dimension. Velocities c_x and c_y are spatial x and y components of the group velocity c_g, the speed at which wave action is transported. c_σ and c_θ are the rate of change in spectral space, which describe the directional (θ) rate of turning and frequency shifting due to changes in currents (u, v) and water depth. Wave propagation on the left-hand side of equation (2) is balanced by local changes to the wave spectrum from energy density source terms S_{tot} on the right hand side, which describes the sources, sinks and distribution of energy in the wave spectrum (Booij et al., 1999). Radiation stresses are determined from spatial gradients in the directional energy spectrum $E(\sigma,\theta)$, the strongest gradients in radiation stress may occur where depth-induced breaking happens (Mulligan et al, 2008).

The ROMS model

The Regional Ocean Modeling System (ROMS) is a fully 3D baroclinic circulation model which solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic and Boussinesq assumptions (Warner et al, 2008). The vertical coordinate is implemented as being a sensible way to handle variations in the water depth. The ROMS equations have been modified to include wave induced momentum flux (horizontal and vertical wave radiation stresses) that are important in near-shore regions by adding depth-dependent radiation stress terms in the three-dimensional momentum equations and depth-independent terms to the two-dimensional momentum equations, neglecting Coriolis, density variations, and scalar transport (Haas and Warner, 2009). The governing equations in Cartesian coordinates are:

$$\frac{\partial(H_z u)}{\partial t} + \frac{\partial(uH_z u)}{\partial x} + \frac{\partial(vH_z u)}{\partial y} + \frac{\partial(\Omega H_z u)}{\partial s} = -H_z g\frac{\partial \eta}{\partial x} - \frac{\partial(\overline{u'w'})}{\partial s} - \frac{\partial(H_z S_{xx})}{\partial x} - \frac{\partial\left(H_z S_{xy}\right)}{\partial y} + \frac{\partial S_{px}}{\partial s} \tag{3}$$

$$\frac{\partial(H_z v)}{\partial t} + \frac{\partial(uH_z v)}{\partial x} + \frac{\partial(vH_z v)}{\partial y} + \frac{\partial(\Omega H_z v)}{\partial s} = -H_z g\frac{\partial \eta}{\partial y} - \frac{\partial(\overline{v'w'})}{\partial s} - \frac{\partial\left(H_z S_{xy}\right)}{\partial x} - \frac{\partial\left(H_z S_{yy}\right)}{\partial y} + \frac{\partial S_{py}}{\partial s} \tag{4}$$

$$0 = -\frac{1}{\rho_0}\frac{\partial p}{\partial s} - \frac{g}{\rho_0}H_z\rho \tag{5}$$

with continuity as

$$\frac{\partial \eta}{\partial t} + \frac{\partial(H_z u)}{\partial x} + \frac{\partial(H_z v)}{\partial y} + \frac{\partial(\Omega H_z)}{\partial s} = 0 \tag{6}$$

where ***u, v*** and Ω are the mean components in the horizontal (*x* and *y*) and vertical (*s*) directions respectively; the vertical sigma coordinate $s = (z - \eta)/D$ ranges from *s*= -1 at the bottom to *s*= 0 at the free surface; *z* is the vertical coordinate positive upwards with *z=0* at mean sea level; η is the wave-averaged free surface elevation; *D* is the total water depth *D*=*h*+ η; *h* is the depth below mean sea level of the sea floor; H_z is the grid cell thickness. An overbar represents a time average, and a prime(‘) represents turbulent fluctuations. Pressure is p; ρ and ρ_o are total and reference densities; g is acceleration due to gravity; and a fuction $\rho=f(C)$ where C represents a tracer quantity (*e.g.* salt, temperature, suspended sediement) is required to close the density relation. These equations are closed by parameterizing the Reynolds stress using one of the five options for turbulent-closure models in ROMS (Hass and Warner, 2009).

In equations (3) and (4) the terms on the left side are: the change rate, horizontal advection and vertical advection; on the right side: surface pressure gradient, vertical viscosity, horizontal radiation and vertical radiation (where the surface roller term is included). Equation (5) represents the hydrostatic buoyancy force and the equation (6) represents the continuity equation. The above equations neglect Coriolis force, density variations and scalar transport, as well as the momentum transfer term that correlates wind-induced surface pressure fluctuations and wave slope. The horizontal radiation stress terms can be seen in full detail in Warner et al (2008) and Hass and Warner (2009).

The coupled system

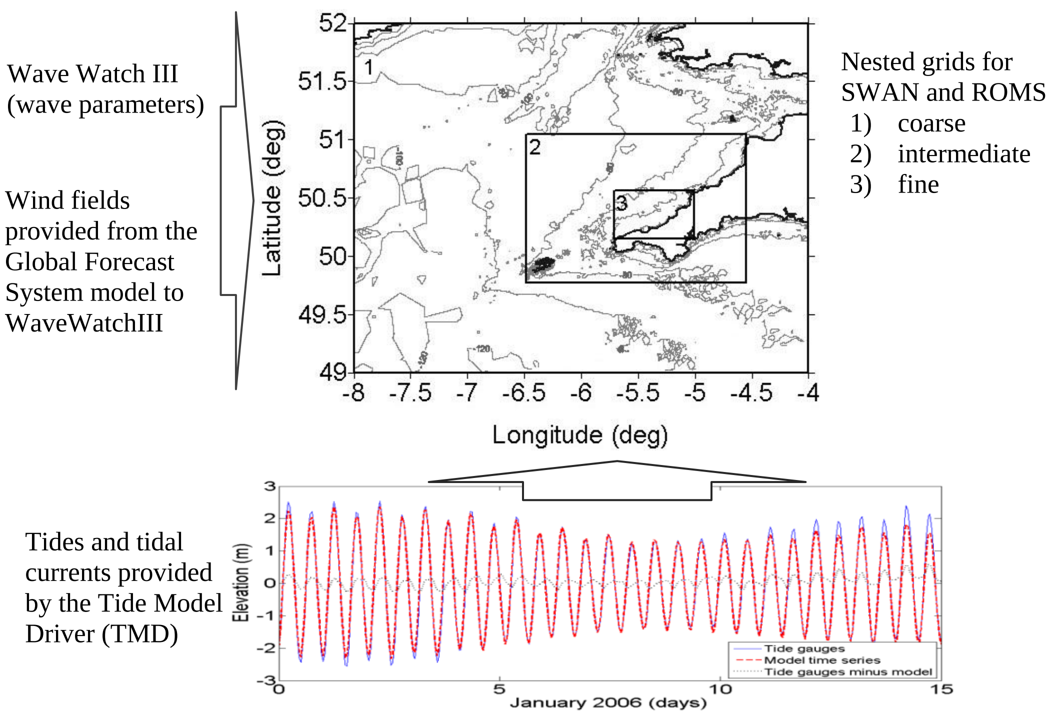

Figure 1. Model boundary conditions and nested grid domains.

The complex numerical modelling system consists of two main open source models; the spectral wave model SWAN and the circulation ROMS model, which are a fully two way coupled, with a sediment transport module embedded system. The modelling system was set in the Wave Hub site. In operation the wave model is fed by the output of the global wave spectral model Wave Watch III (NOAA http://polar.ncep.noaa.gov), wind fields are provided from the Global Forecast System (GFS) model to WaveWatch III model, then, a tidal model provides tidal currents and water elevations to both SWAN and ROMS wave and circulation models. As shown in Figure 1, the coupled modelling system was run with three nested domains with a progressively finer grid resolution. In addition, a sediment transport model was incorporated in the modelling system for computing beach morphological changes, the results of which, however, are not discussed in this paper.

The wave model needs water elevations and tidal currents on the whole domain (not as boundary conditions), the circulation models requires tidal currents and water elevations to be forced as boundary conditions. The Tide Model Driver (TMD), a tidal prediction software through the Artic Ocean Tidal Inverse model (Padman and Erofeeva, 2004) based on the TOPEX/POSEIDON altimeter data, was used to obtain predictions of tidal currents and water elevations from eleven harmonic constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_4, MS_4, MN_4) for the studied area. At the bottom of the Figure 1 the predicted elevations and tidal currents are shown and they are in a good agreement with tide gauges. The test period for the study was from 1st to 31st January of 2006 with the available wave buoy data.

RESULTS

Model tests were first carried out with the SWAN model setting conditions of variation of tidal levels, tidal currents and constant wind. It was observed that normal conditions have a quicker numerical stabilisation rather than the extreme conditions, also it was observed a non-steady state produced by currents and water elevations.

Figure 3 shows the effect of tidal currents on spatial wave heights for the fine grid domainfor spring tides at high tidal level (top) and low tidal level (bottom). With tidal currents, the computed significant wave heights at the Wave Hub are higher by approximately 0.4 m in comparison with those computed without tidal currents at high water level. However, at the low tidal level, the magnitude of the increase is smaller, in a range of about 0.2 m.

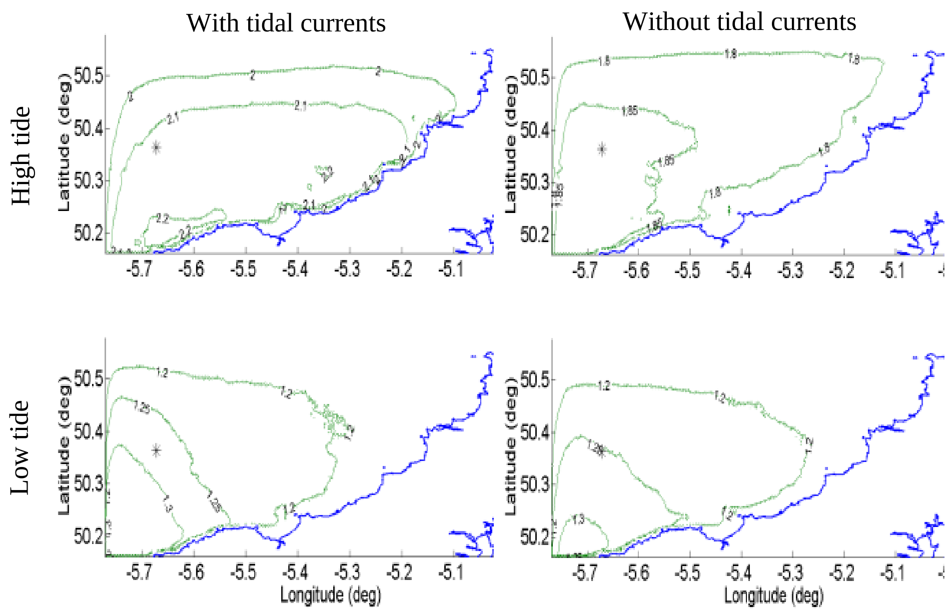

Figure 2. Snapshots of contours of the fine nested grid at the Wave Hub region at spring tide. (Left) Significant wave height (m) with tidal currents. (Right) Significant wave height (m) without tidal currents. (Top) High tide. (Bottom) Low tide. (*) Wave Hub site.

Bed shear stress

To understand the sediment transport due to waves and currents, it is necessary to calculate the bed shear stress (Wolf and Prandle, 1999). These results generate a wave-induced current and additional drift (long-shore current) (Figure 6), typically along the coast (Pleskachevsky et al, 2009).The water depth influences the wave: low tide affects the waves more due to bottom influence than in high water.

The next test-cases take into account analytical waves which were provided to the circulation model to interact with the tidal currents, analytical stands for wave parameters imposed as constant boundary conditions. Three main cases of wave and current interactions have been tested: firstly, with the influence of tidal currents only; secondly, tidal currents and the influence of analytical waves and; thirdly, currents, waves and analytical wind stress.

For further model tests, both tidal elevation and currents are included together with the wave-induced current. Figure 3 shows that the depth-averaged long-shore and cross-shore components of current velocities at the Wave Hub site. For the sake of clarity, the computed current velocities have been decomposed into long shore and cross-shore directions based on the main direction of the shoreline at the site, neglecting the vertical structure of the horizontal velocities.

As shown in Figure 3, the velocities computed for tide only and combined tide and wave without wave-current interaction are found to be almost identical. However, when the wave-current interaction is included, the computed velocities are clearly enhanced, particularly for the long shore component. By removing the underlying tidal velocity, the impact of wave-current interaction on the computed current velocities is clearly illustrated during the spring tides, as shown in Figure 4.

The anomalies of the currents were calculated using a least square method (harmonic analysis), so that the general tidal variation can be removed. Figure 5 shows the kinematic bottom stresses. Similar as velocities, the long-shore component at a spring tide has major impacts on the bed shear rather than the cross-shore component.

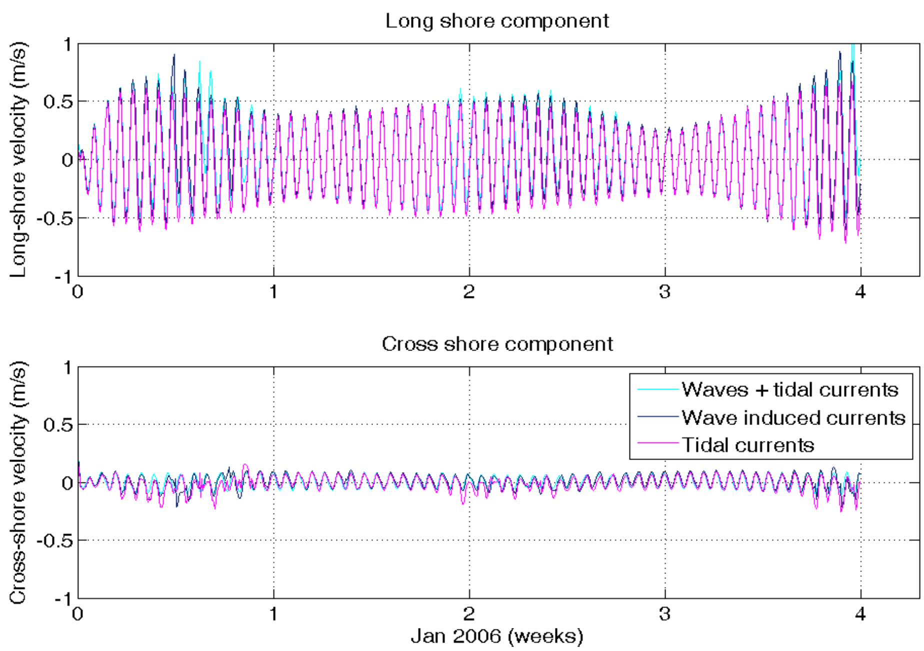

Figure 3. The long-shore and cross-shore components of the current velocities at the Wave Hub site. The legend at the bottom applies for the two figures.

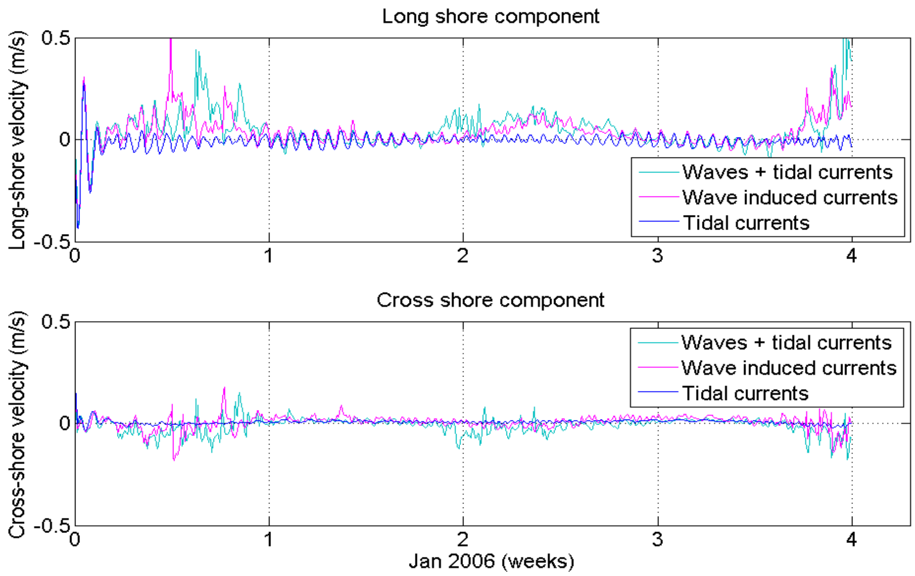

Figure 4. Anomalies of the current velocities for long-shore and cross-shore components, at the Wave Hub site.

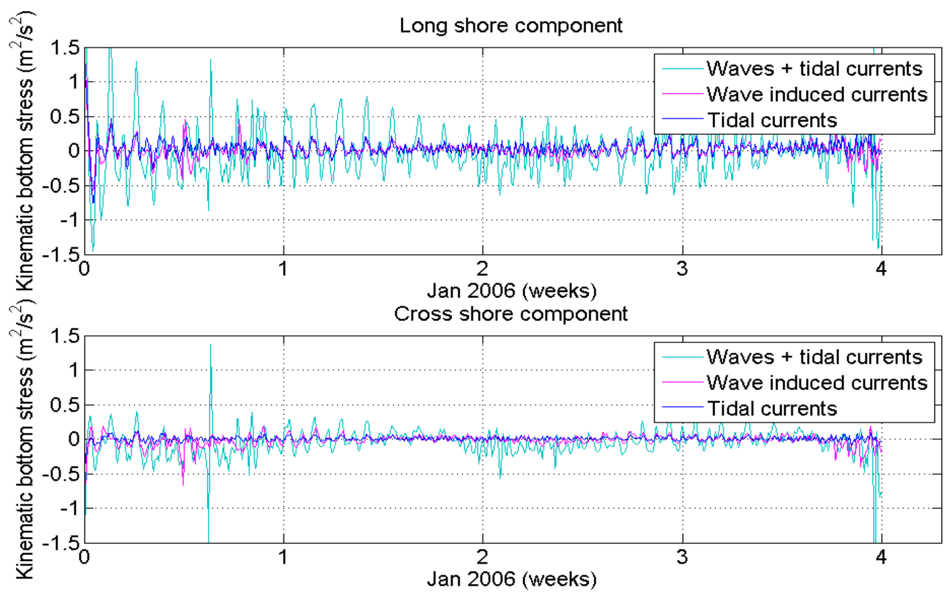

Figure 5. Anomalies of the kinematic bottom stress for long-shore and cross-shore components, at the Wave Hub site.

Wave effects on tidal currents (radiation stress influence)

In order to study the wave-tide interactions the concept of radiation stress must be included, which is the flux of momentum carried by the ocean waves, when these waves break, that momentum is transferred to the water column, forcing near-shore currents. Radiation stress theory has been successfully used to explain the presence of long-shore currents (Bowen, 1969). Significant momentum can be transferred from wave to current especially where strong radiation stress gradient occurs due to breaking and bottom friction in the near-shore region.

Figure 6 shows a snap shot of current velocities with (left) and without (right) radiation stress influence, again the long-shore component has more impact on the general circulation of the area of study. It is worth mentioning that for these cases the surface stress has been idealised over the whole domain.

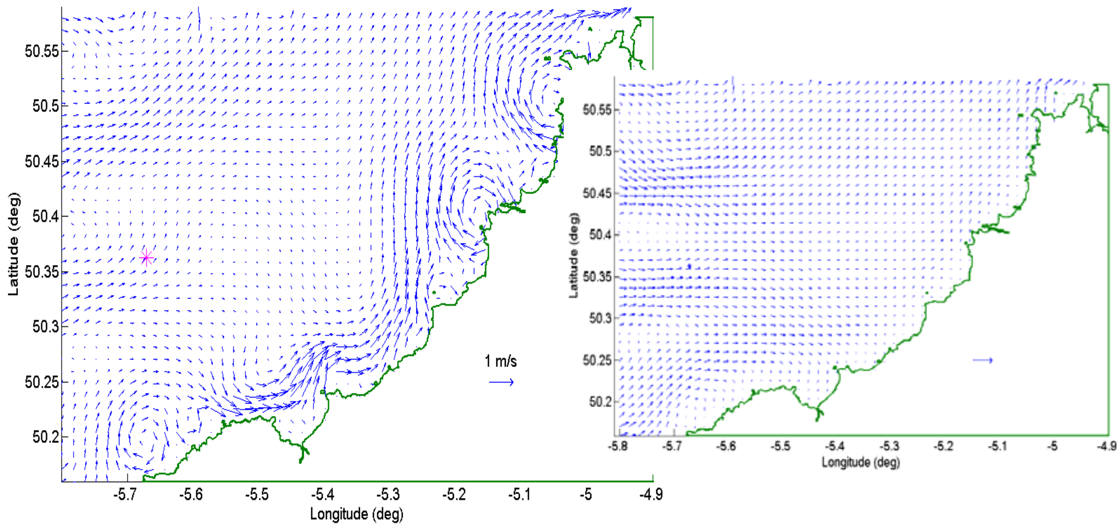

Figure 6. Velocity currents with (left) and without (right) radiation stress influence.

To assess the impact of waves on tidal currents a series of different cases combining spring and neap tides, high and low waters, high and low wave conditions, were tested to obtain current velocities and bottom stresses. In Figure 7 the significant wave height is plotted for the SWAN case only and for the coupled system against the sea surface elevation and buoy observations.

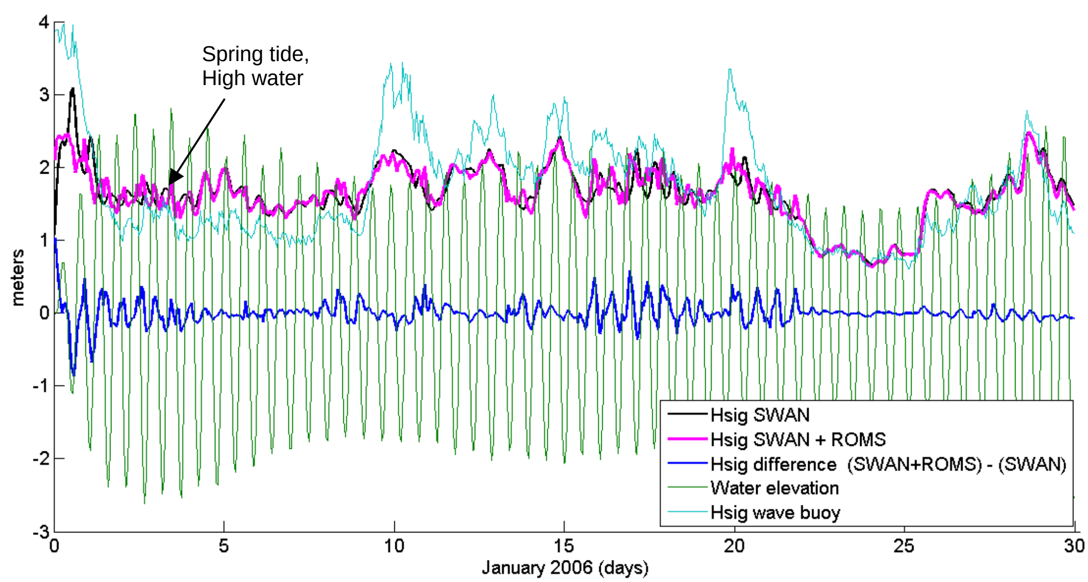

Figure 7. Significant wave heights with and without tidal currents and water elevations effects

In order to see the effects of waves on tidal currents, the change of currents or the magnitude of the velocity differences with and without the wave influence, the following formulation was applied to the velocity field:

$$V_{diff} = \sqrt{\left(U_{wy} - U_{wn}\right)^2 + \left(V_{wy} - V_{wn}\right)^2} \qquad (7)$$

where U_{wy} and U_{wy} are the x-horizontal velocity components with wave interaction and without wave interaction, respectively. V_{wy} and V_{wn} similarly for y-horizontal velocity components.

In Figure 8 the magnitude of velocity differences is shown, notice that in the near-shore region waves have a major impact on current velocities close to 1m/s of difference, in a similar way, the bottom stress difference has been mapped Figure (10), as well as velocity differences, the waves have the greatest impact on the bottom stress for the case indicated in Figure 7.

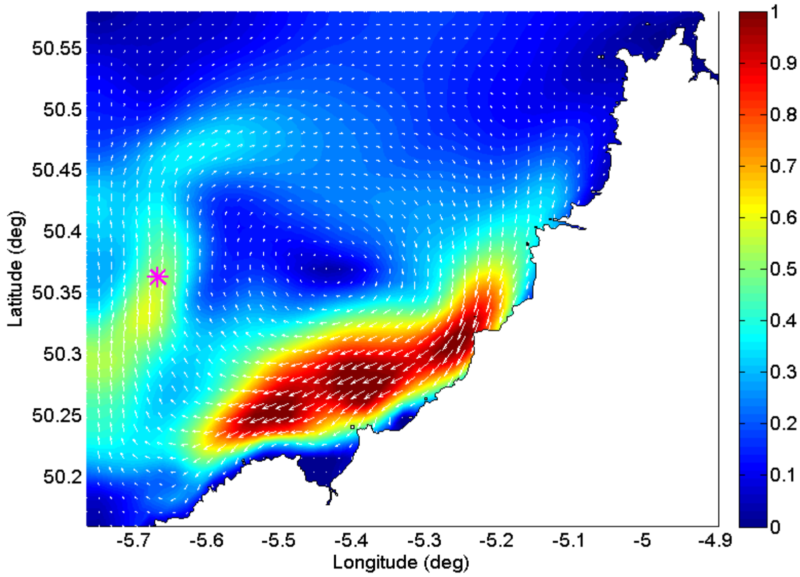

Figure 8. Current differences between ROMS+SWAN and ROMS for the point indicated by the arrow in Figure 7.

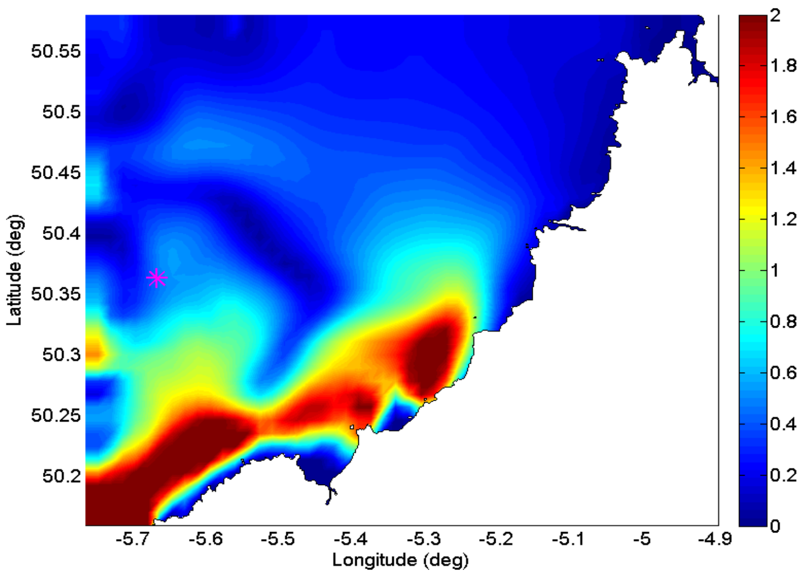

Figure 9. Bottom stress differences between ROMS+SWAN and ROMS for the point indicated by the arrow in Figure 7.

CONCLUSIONS

The wave model has been nested from coarse to fine grids, as shown in Figure 1, it has been forced by wave parameters and wind fields from global models. Model results have been compared against tide gauges and wave buoy observations with reasonable agreement. The circulation model has been forced by the tide model and wave parameters as radiation stress from the wave model. Also wind induced waves has been tested to improve the wave-current effect on the bed shear stress and velocity current fields.

The tidal elevation and tidal currents have a significant effect on the wave height predictions, tidal currents and wind waves have a significant effect on the bed shear-stress, relevant to sediment transport.

Waves via radiation stresses have an important effect on the long-shore and cross-shore velocity components, particularly during spring tides. Waves can impact on the bottom boundary layer and the mixing in the water column.

Significant wave heights are improved when the coupled modelling system is implemented. Also velocity currents and bed shear stresses show the significant influence from waves via radiation stress.

Interaction between waves and tides at the Wave Hub site is important when modelling sediment transport influenced by wave energy devices. The addition of wind fields on the circulation model are compulsory to determine the effect of surface stresses on waves and currents, moreover, the sediment transport study is being implemented in future works.

The results of this study will help the wave energy resource assessment and potential environment impact of the wave farm. Model results will be validated against the wave and current measurements by HF RADAR, ADCP and Directional Waverider buoys during the on-going Wave Hub projects.

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