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The impact of a wave farm on large scale sediment transport

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Abstract— **This study investigates the interactions of waves and tides at a wave farm in the southwest of England, in particular their effects on radiation stress, bottom stress, and consequently on the sediment transport and the coast adjacent to the wave-farm (the Wave Hub). In this study, an integrated complex numerical modelling system is setup at the Wave Hub site and is used to compute the wave and current fields by taking into account the wave-current interaction, as well as the sediment transport. Results show that tidal elevation and tidal currents have a significant effect on the wave height and direction 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 longshore and cross-shore velocity components, particularly during the spring tides. Waves can impact on bottom boundary layer and mixing in the water column. The results highlight the importance of the interactions between waves and tides when modelling coastal morphology with presence of wave energy devices.**

Keywords— **Wave Hub, Wave-tide interaction, Sediment transport, SWAN, ROMS**

I. INTRODUCTION

The Wave Hub project aims to create one of the world's largest wave farms for demonstration and testing wave energy converter devices, located at the southwest coast of England, as shown in Fig. 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 study by SWRDA (2006) based on numerical modelling suggests that the wave energy converters (WECs) installed at Wave Hub would cause a reduction between 3% - 5% of wave height in the near coast of the Wave Hub, as well as changes in tidal currents and bathymetry. In their study the hydrodynamic model, Flow3D, was forced by four tidal constituents during a storm to assess the impact of the deployed WECs on tidal currents and sediment transport. Wave buoy data from 3 to 14 Feb 2005 was used in the model calibration. Tidal currents recorded maximum current velocities of 1.2 m/s. The admiralty pilot reports tidal currents between 0.5 and 1.0 m/s on the north coast of Cornwall during spring tides. To assess the WECs effect on the studied area, wave dragon devices were used as the worst case scenarios. Model results show that sediment transport for the worst case scenario changes significantly at the Wave Hub site, but the impact of the wave farm on the adjacent nearshore zone remains an unresolved issue. Millar *et al* (2007) carried out a study at the Wave Hub site to estimate the impact of WECs on the nearshore wave climate by analysing the wave energy transmitted through the WECs to the adjacent nearshore region. By comparing the SWAN model results with field observations from wave buoys, they concluded that assuming a 90% transmission rate, 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 that are close to the Wave Hub site.

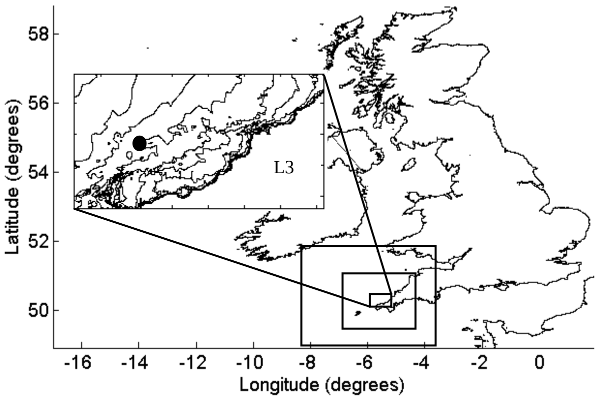

Fig. 1 SWAN nested grids (squares); SWAN+ROMS coupled system domain (L3), Wave Hub site (●).

From the perspective of the impact on this stretch of coast, the sand transport due to tides is believed to be weak and unquantified in this region, and the volume of sand involved is limited in comparison with other sectors of the English coasts. Therefore, wave induced currents are more important in controlling sediment movement. The prevailing winds are from the South and West, but easterly winds can also produce significant movement of sediment. Although storm events

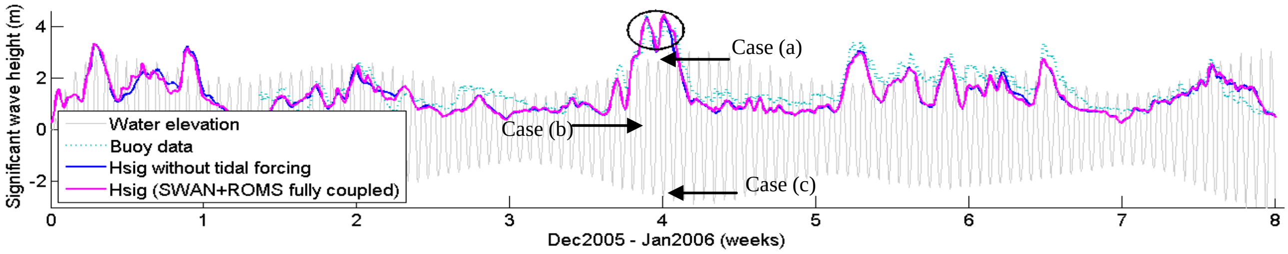

Fig. 2 Significant wave heights with/without tidal influence. Circle represents maximum storm Hsig at spring tide. Three main cases have been analysed at the peak of the storm event indicated by the circle: at high water elevation and low current velocity (Case a); at middle water level and high current velocity (Case b); and at low water elevation and low current velocity (Case c).

may cause movement of sand on the inner shelf, their effects are greater in the nearshore zone where significant cross- and long-shore sediment transport takes place (Buscombe and Scott, 2008). Clearly, there is a lack of studies in the nearshore and shoreline areas in the lee side of the wave farm, thus, the aim of this study is to investigate the wave-tide interactions, in particular their effects on sediment transport along the coast behind the wave-farm. We examine the tidal effects on wave, wave-induced currents, radiation stresses and bottom stresses, using a complex wave-current coupled numerical modelling system to gain insight into how wind waves and tidal currents affect the current and bottom friction at the Wave Hub site and the adjacent nearshore zone.

II. THE MODELLING SYSTEM

In this study, the spectral wave model SWAN (Booij *et al*, 1999) and the flow circulation model ROMS are used to form a fully two-way coupled modelling system (Warner *et al*, 2008). As shown in Fig. 1, the SWAN model is run with three nested domains with progressively finer grid resolutions. At the finest grid (L3), the SWAN is coupled with the ROMS model to form the coupled modelling system (SWAN+ROMS). The SWAN model is fed by the output of the global wave spectral model Wave Watch III (NOAA: *http://polar.ncep.noaa.gov*) driven by the wind fields from the Global Forecast System (GFS) model. The global tidal model OTPS (Egbert *et al*, 2002; Padman and Erofeeva, 2004) provides tidal currents and water elevations as boundary conditions for the ROMS model. The wave model results can be affected by both water elevations and tidal currents, hence, the tidal information obtained from the ROMS model is used in the wave model.

The tidal model used is the Oregon State University Tidal Prediction Software (OTPS/TPXO) based on the TOPEX/POSEIDON altimeter data (Egbert *et al*, 2002; Padman and Erofeeva, 2004), which 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). We found that the predicted water elevations are in a good agreement with the measurements from tide gauges near to the Wave Hub site.

In addition, a sediment transport model embedded in ROMS was incorporated in the modelling system for computing sediment transport for beach morphologicaL changes. The Soulsby and Damgaard (2005) formulae is applied for computing bedload transport which accounts for the combined effects of mean currents and asymmetrical waves on bedload flux. The bed model accounts for changes

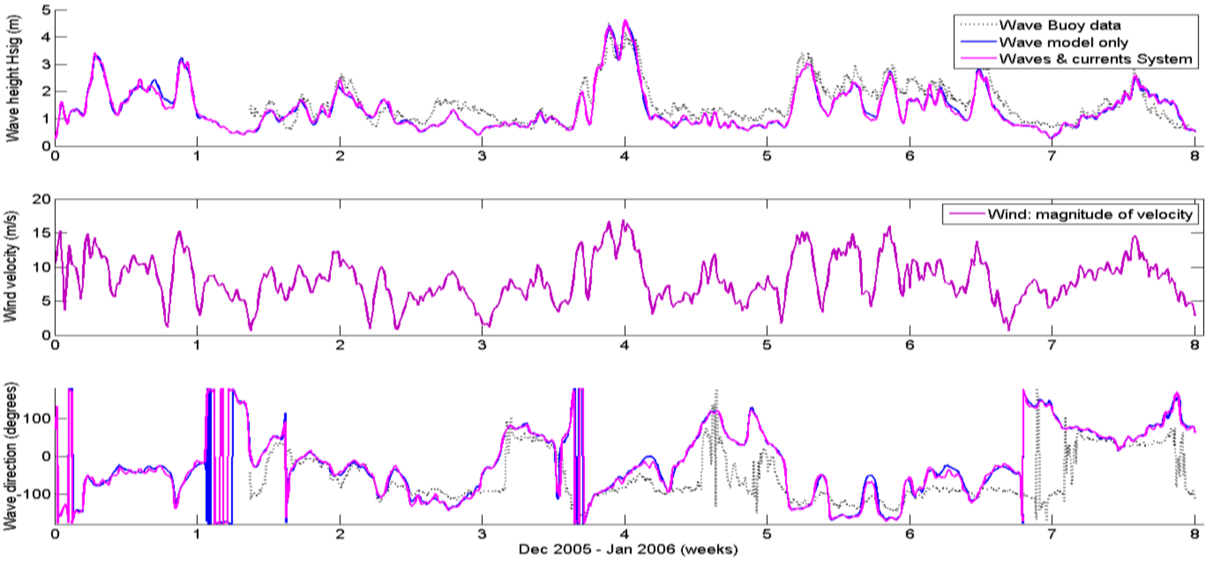

Fig. 3 Time series at the Wave Hub site of significant wave height (top), magnitude of wind velocity (middle), and wave direction (bottom), for the wave-current interaction and waves only. Note the strong correlation between the wind, the significant wave height, and the wave direction.

in sea floor elevation resulting from convergence or divergence in sediment fluxes. These morphological changes can have an impact on flow transport when they are larger (Warner *et al*, 2008).

The coupled modelling system (SWAN+ROMS) was applied to assess the impact of waves on tidal currents and tidal currents on waves. To achieve this, a series of different cases combining spring and neap tides, high and low water levels, high and low wave conditions, were investigated to examine the changes in wave parameters, current velocities and bottom stresses.

The two-way coupled modelling system consists of two models which are linked with shared information: the ROMS model, which computes sea surface levels, depth averaged horizontal velocity components and bottom stress based on the given sediment grain size; and the SWAN model, which computes wave height, wave length, wave period and wave bottom orbital velocities. Between these two models, the currents and water levels computed in ROMS are used in SWAN and the radiation stresses derived from the SWAN are used to calculate the wave induced current in ROMS, so that the dynamic interaction between waves and tides is realised. In addition, wind fields are used as the surface forcing in the SWAN model for predicting the wave field, but, the wind stress is ignored in the ROMS model due to the relatively small computational domain.

III. RESULTS

A. Wave-tide interaction

The modelling system was run for two months, from 1st December 2005 to 31st January 2006 due to the availability of wave buoy data. Three test cases were selected to examine the space distribution of wave-tide interactions through the tidal cycle. These test cases are selected at the peak of the storm and during spring tide: Case (a) High water level and low current velocities; Case (b) Middle water level and high current velocities; Case (c) Low water level and low current velocities.

Fig. 2 shows the influence of tidal currents and tidal elevations on the significant wave heights at the Wave Hub site predicted by the coupled system, compared with buoy measurements. Fig. 3 shows the differences, with and without tidal currents, of the significant wave height and wave direction for the cases indicated above within the L3 domain (see Fig. 1). This figure shows the difference between the coupled modelling system and the wave model only for the significant wave height and wave direction, but mostly the strong correlation of wave height, wave direction and wind velocity, suggesting that wind waves play an important role on the longshore currents and therefore on the sediment transport. The wave direction oriented more along the shore would produce stronger alongshore currents, for example during the low water level case. When tidal currents are included, the wave direction is modified by less than 10 degrees during high waves, but about 20 degrees during low waves.

In order to study the wave-tide interactions, the concept of radiation stress is included, which is the flux of momentum carried by the ocean waves. When these waves break, the wave momentum is transferred to the water column, inducing 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 waves to currents when a strong radiation stress gradient occurs due to wave breaking and to the bottom friction in the near-shore region. Radiation stress gradients are determined from the spatial gradients in the directional energy spectrum of the wave model and the strongest gradients in radiation stress occur where depth-induced breaking happens (Mulligan *et al*, 2008).

Waves and currents are coupled through the following physical mechanisms: i) surface shear stress, the effect of surface waves on the drag coefficient is included in ROMS (Warner *et al*, 2008); ii) bottom stress, waves enhance the turbulent mixing, therefore, waves modify the bottom stress experience by currents (Grant & Madsen, 1979; Zou, 2004); and iii) radiation stress which represents the excessive momentum flux within the circulation due to the presence of waves (Longuet-Higgins and Stewart, 1964).

Comparisons between surface current velocities at the Wave Hub site from the coupled modelling system (SWAN+ROMS) and the circulation model (ROMS) were carried out. These comparisons are shown in Gonzalez-Santamaria *et al* (2011), the results indicate that the impact of wave-current interactions on the computed current velocities is significant during the spring tides. Similar to the current velocities, both

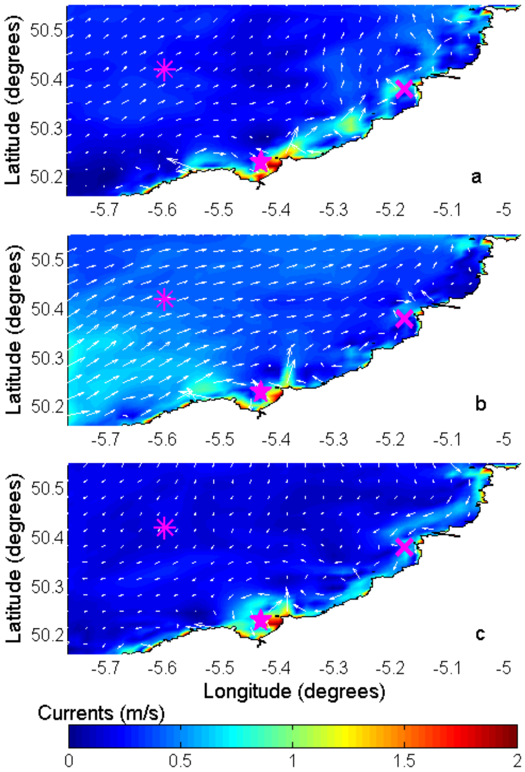

Fig. 4 Spatial distribution of bottom current velocities (ROMS+SWAN fully coupled) for the cases indicated in Fig. 2: high water elevation (a); mid water elevation (b); low water elevation (c).

Wave Hub site (*), St Ives bay (★) and St Agnes (×).

components of the current-induced bottom stress in a spring tide are significantly affected by the waves. As waves propagate towards the coast, the wave propagation speed and direction may be modified by tidal currents due to refraction. In general, the main changes of wave direction are found during low wave heights and high tidal currents. Three reference sites shown in Fig. 4 for further comparisons are the Wave Hub site, St Ives bay and St Agnes. It was found that at the Wave Hub site the current magnitudes, after removing the tidal signal, are smaller than those at St Ives bay and St Agnes where the wave action enhances the current significantly. At St Agnes, the longshore currents vary from -0.5 to 0.5 m/s, and at St Ives bay, longshore currents vary from -0.5 to 1.1 m/s. This is the result of wave propagation direction relative to the shoreline at this site.

The spatial distribution of the wave influence on bottom currents is shown in Fig. 4 where larger velocities and eddies are observed along the coast which are up to 2 m/s. In Case (a), when the water elevation is high but with low tidal currents, the region with significant wave induced currents is more confined to the coast. In Case (b) for middle water level, tidal currents are at its maximum, and the total current velocity field is uniform in the offshore zone and increases in magnitude in the nearshore zone where the significant wave height is high. In Case (c), water elevations and tidal currents are both in minimum, the region with significant wave induced currents is extended in the offshore direction due to decreasing water depth.

The velocities near the coast, predicted by the fully coupled modelling system, are clearly enhanced by the wave forcing, particularly in the longshore direction. In St Ives bay, this effect is the most significant (Fig. 4).

When tidal currents and wave induced currents are coupled, the currents field at the Wave Hub site increases significantly, compared with the results when there is no wave interaction. The total current is dominated by the tidal currents which are more uniform away from the coast. However, along the shoreline, currents are enhanced by the wave action through radiation stress. This means that wave induced currents are significant in this zone, even though the tidal currents are the main force for the general circulation.

B. *Wave farm effects*

The wave farm was set in the SWAN model as suggested in Millar *et al* (2007), arrays of WECs at the Wave Hub site represented as a 4km partially transmitting obstacle, aligning approximately parallel to the incoming wave crests. The energy transmission percentage was set as 75% which represents an array of densely spaced, high-efficiency WECs.

Fig. 5 shows significant wave height (colours) and wave direction (vectors) for the storm case and for the tidal cycle cases. In this figure the difference between the wave-current interaction against the wave-current and wave farm interaction is shown. The change of the wave height with and without the wave farm is between 5cm and 10 cm at the nearshore line, and the maximum extension affected by the wave farm is about 26km from St. Ives Bay to upwards for the high water level case which is the most significant in terms of wave height variations.

Fig. 6 shows the bottom stress contribution by waves (left) and by tides (right) for the tidal cycle cases. The wave contribution on the bottom stress is large compared to tides only, driving the sediment transport at the most and during the storm peak.

Fig. 7 shows the combined wave-current bottom stress (left panels) at different water levels during the tidal cycle, as well

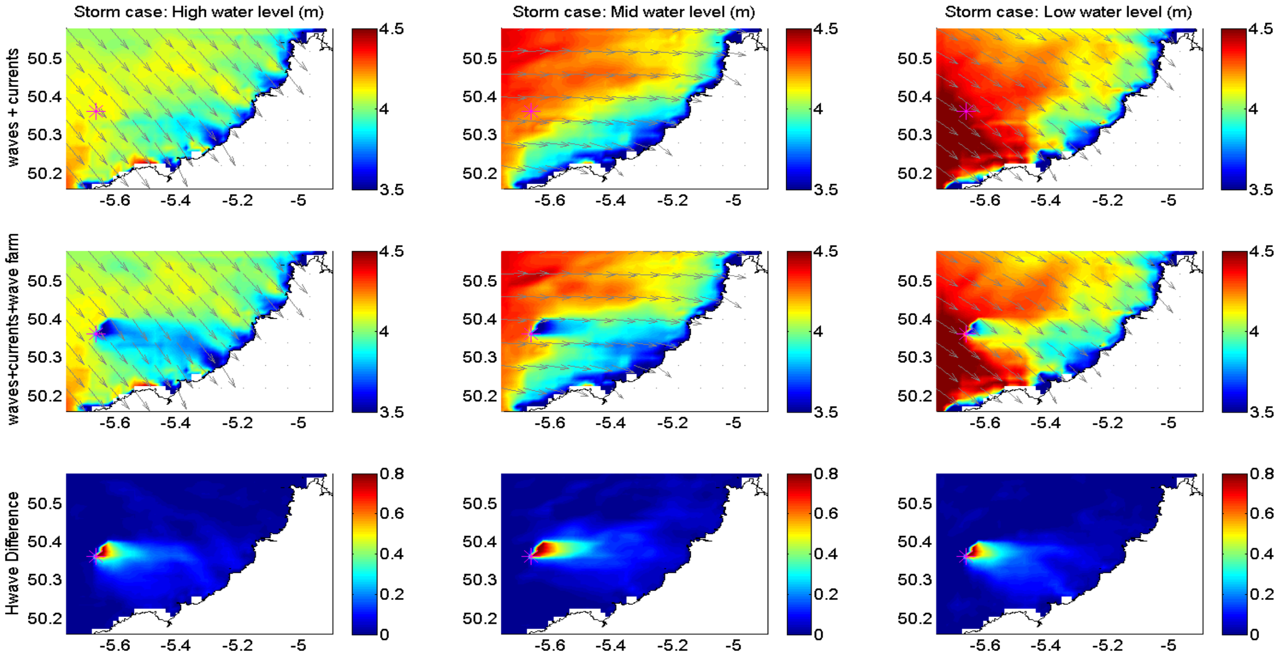

Fig. 5 Significant wave height (colours) and wave direction (vectors) for the storm case and for the tidal cycle cases. In this figure is shown the difference (bottom panels) between the wave-current interaction (top panels) and the wave-current & wave farm interaction (middle panels). Wave Hub site (*).

as the velocity vectors because both magnitude and direction are important when correlating wave induced currents. The bottom stress is also correlated with the currents field for Cases (a) to (c) and is affected by the local water depth. The region with significant bottom stress is confined to the shallow water region and moves towards/away from the coast when the water level decreases/increases during the tidal cycle. Case (c) shows maximum bottom stress along the coast because of lower water elevation, Case (a) shows smaller bottom stress because of the high water elevation. The bottom stress difference with and without the wave farm (right panels) shows the most significant variation for the low water level case, which is strongly correlated to the currents field, waves and depth.

C. Sediment transport distribution

Fig. 8 shows the non-cohesive sediment (sand) concentration (kg/m^3) for the fully coupled system (left panels) and the difference with and without the wave farm effect (right panels). Here the Case (c) is the most significant as the sediment transport changes as the tidal cycle varies during the storm peak. As expected, the bottom stress has a strong correlation with the sediment distribution, for the low water level case; however, when the velocity current is close to zero (top and bottom panels) the wave farm has an effect on the sediment distribution and this is directly correlated to the wave contribution. The wave contribution is driven mainly by the wind. The observed changes in sediment concentration with and without the wave farm are up to 0.002 kg/m^3 at St. Ives Bay for the variation of the tidal cycle. As the tidal cycle varies the sediment concentration extends about 26 km upwards from St. Ives Bay for the high water level case which has larger effects. On the other hand, at the low water level case, the sediment concentration moves in some offshore areas, mainly in the lee of the wave farm.

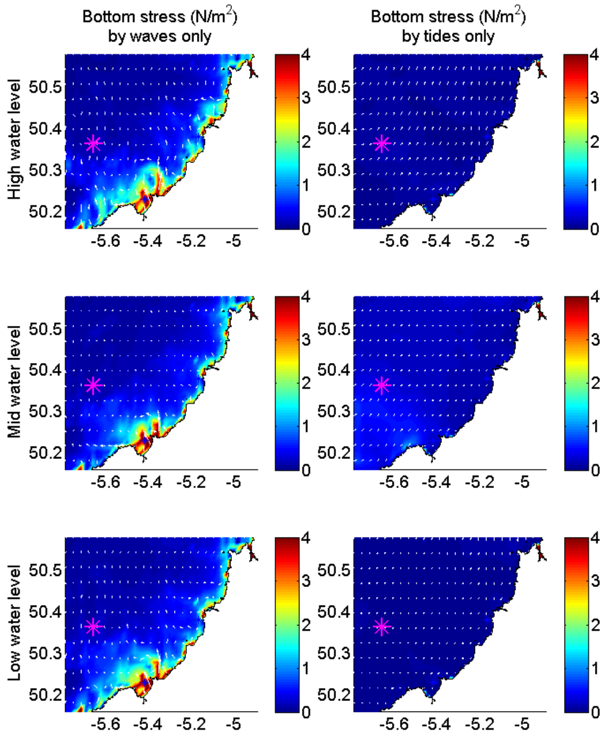

Fig. 6 Bottom stress comparisons by waves (left) and by tides (right) only, and velocity vectors (arrows) for the tidal cycle cases. Wave Hub site (*).

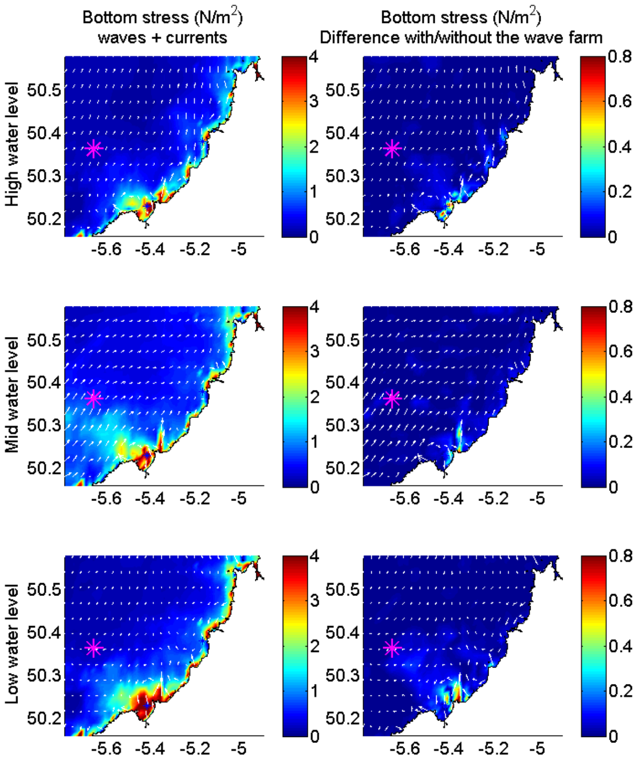

Fig. 7 Bottom stress differences, for the full wave-current interaction, with and without the wave farm and velocity vectors (arrows). Note that for the case of low water level, the wave farm has a significant effect on the bottom stress. Wave Hub site (*).

IV. CONCLUSIONS

In this study, a two-way coupled modelling system with the SWAN and ROMS models has been used to study the wave-current interaction and the impact of the Wave Hub site on the nearshore area, a wave farm in the South West of England. The wave model, SWAN, was nested from coarse to fine grids, forced by the spectral wave model Wave Watch III and wind fields from the GFS model. The circulation model, ROMS, was forced by the tide outputs from the global tidal model OTPS and by the wave forcing from the SWAN model on the fine grid. The sediment transport model was incorporated to estimate the non-cohesive concentration affected by waves, tides and the wave farm. Model results are in good agreement with the measurements by tide gauges and wave buoy.

Model results at high, middle and low tidal levels during the peak of a storm were presented to show tidal effects on waves, current velocities and bottom stresses, during spring tides. It is found that the wave height increases with the tidal elevation, and the wave direction is modified by the change of direction of tidal currents. We also found that the tidal current effect on waves is at maximum at middle and low

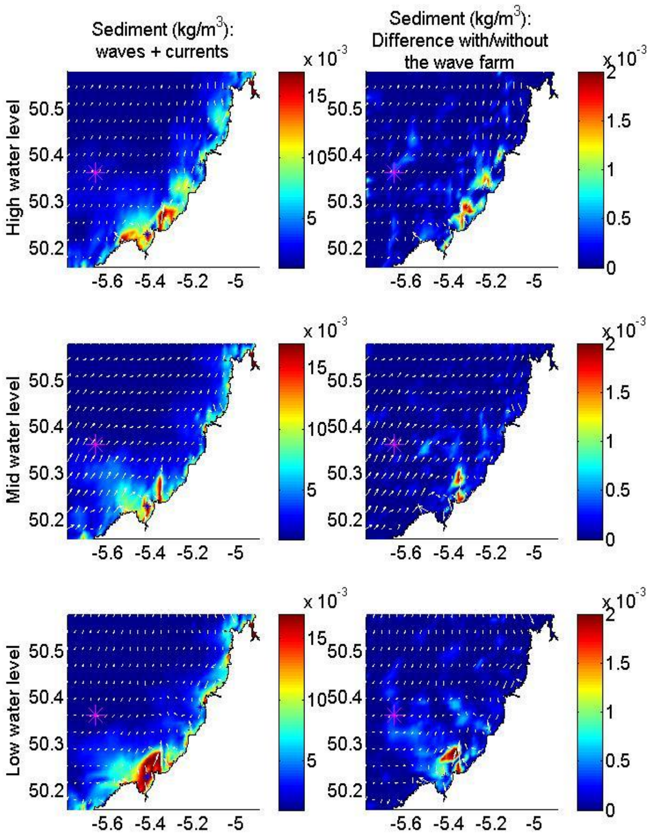

Fig. 8 Sediment transport distribution (colours) and velocity vectors (arrows) for the tidal cycle cases (left panels), and the difference with and without the wave farm (right panels). Wave Hub site (*).

tides when the tidal current is at its peak and the tidal elevation change has a significant effect on wave directions. The tidal current effect on wave direction is relatively small when wave height is large.

Wave effects on currents are isolated by removing the tidal signals from current velocity and bottom stress. Model results show significant cross- and long-shore wave induced currents along the shoreline, which is at its peak at mid-tide with maximum tidal currents and at peak wave heights. Wave induced current is negligible at the Wave Hub site. Uniform current field at the Wave Hub site are observed with and without wave forcing.

The bottom stress becomes larger at low tide and high wave, and also at mid-tide and high wave. This change occurs not only in the nearshore zone but also in some parts of the offshore area, which suggest that sediment transport changes significantly during the tidal cycle and storm peak.

The change of the wave height with and without the wave farm varies between 5cm and 10 cm at the nearshore area, and the maximum extension affected by the wave farm is about 26km from St. Ives Bay to upwards at the high water level case.

The bottom stress difference with and without the wave farm shows significant variations at the low water level case, strongly correlated to the wave contribution through radiation stresses.

The observed changes in sediment concentration with and without the wave farm are up to 0.002 kg/m^3 at St. Ives Bay. As the tidal cycle varies the sediment concentration has larger effects at the high water level case, with maximum extension of 26 km upwards from St. Ives Bay. At the low water level case the sediment concentration moves in some offshore areas, this effect is closely correlated to the bottom stress results.

The results of this study provide important and useful information for further studies in assessing the resources of wave energy and the impacts of the wave farm on the local and nearshore environment. Model results will be further validated against wave and current measurements by HF RADAR, ADCP and Directional Waverider buoys taken during the on-going Wave Hub project.

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