The effect of different levels of coupling in surface wind waves along the NWS during extreme events

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Executive Summary

The Met Office is continuously developing and updating the configuration of its northwest European continental shelf atmosphere, ocean and wave models in order to obtain a more accurate forecasting system. Multiple efforts have been put into development of coupled systems capable of integrating atmosphere–wave–ocean boundary exchanges. The most up to date configuration of the regional coupled research system, herein UKC4, includes models of the atmosphere (Met Office Unified Model), land surface with river routing (JULES), shelf-sea ocean (NEMO) and ocean surface waves (WAVEWATCH III®) coupled using OASIS3-MCT libraries. Although prediction of some fields can be degraded, multiple benefits from using the coupled approach relative to the individual models in forced mode have been demonstrated, in particular those involving wave–ocean feedbacks (Lewis et al., 2019a,b).

This report documents the impact of the coupling between wind wave, ocean and atmospheric models on the wind and wave fields across the northwest European continental shelf (NWS) during a period of severe storms, when some of the largest differences between models employing different levels of coupling might be expected to occur. Two coupled experiments (atmosphere–wave–ocean and ocean–wave) of 4 months of duration are compared against the uncoupled wave only control simulations using both the research and the operational configurations (the latter with wind and currents as forcing). The set of model runs analysed here encompasses the 2013/2014 winter, which in terms of sea and coastal conditions was the most stormy and extreme period affecting the Atlantic coast of the UK in the last 60 years (Masselink et al., 2016). Coupled models (atmosphere–ocean–wave and ocean–wave) show the best skill score in sheltered coastal locations where the wave conditions are overpredicted by the wave–only simulations. However, the fully coupled model consistently under-predicts the wave growth (increase in significant wave height bias of 1–3% and ~5% MSE; MSE increases 5–20% for wind speed) for locations across the NWS where fetch dependence is an important factor (i.e., seas at the E of Ireland and UK for storms coming from the NW-WNW). Results for the ocean–wave coupled model run are very similar to the waves standalone model experiment using global winds as forcing; however, ocean–wave coupling slightly improves model performance in areas with significant tidal modulation such as English and Bristol Channels. When comparing ocean–wave coupled and the waves standalone operational configuration (wind and current as forcing), the current operational configuration shows slightly better overall skill scores, but this is simply associated to suite discrepancies. Hence, the ocean–wave coupled model together with the waves standalone operational configuration appears to be the best compromise concerning

overall model performance. Regarding the forecast of rapidly developing waves on the shelf using the fully coupled system, additional testing is recommended implementing alternative designs of the wave model set-up (e.g., source terms parameterization) and a possible modification of the coupling of momentum between the atmosphere and the wave models.

1. Introduction

Met Office (MO) efforts are always focused on providing more accurate forecasting systems, based on a continual development of the science and numerics underpinning global and regional atmosphere, ocean and wave model configurations. In recent years this process has included the introduction of coupled systems designed to reproduce the physical interactions between the atmosphere, ocean and wave components. The most recent configuration of the regional coupled research system for the UK and northwest European continental shelf seas, herein UKC4, includes models of the atmosphere (Met Office Unified Model), land surface with river routing (JULES), shelf-seas ocean (NEMO) and ocean surface waves (WAVEWATCH III®) which are coupled using OASIS3-MCT libraries (for a detailed description of UKC3 refer to Lewis et al., 2019b).

Multiple benefits from using varying coupled approaches (ocean–wave, atmosphere–wave or atmosphere–ocean–wave) relative to the individual models in forced mode have been demonstrated. Several studies using ocean–wave coupled models highlight the positive changes in significant wave height in the presence of surface ocean currents (Osuna and Monbaliu, 2004; Hersbach and Bidlot, 2008; Fan et al., 2009; Palmer and Saulter, 2016; Lewis et al, 2019b). Additionally, it has been demonstrated that the coupling between an atmospheric model and a wave model provides better estimates of the roughness lengths over the oceans, with a subsequent improvement in model simulations of wind speed and significant wave height (Janssen and Viterbo, 1996; Janssen et al., 2002; Wahle et al., 2017; Wu et al., 2017; Wiese et al., 2019). Wahle et al. (2017) confirmed complimentary improvements in both wave and wind forecasts in coastal regions of the southern North Sea by implementing a two-way coupling between the wave and the atmosphere model. They found that significant wave height and wind speeds were reduced by approximately 8 % and 3 %, respectively, due to the extraction of energy and momentum from the atmosphere by waves. Varlas et al. (2017) found that coupling impacts the evolution of the system, with similar reductions in wind speed and wave height to those discussed by Wahle et al. (2017).

Prediction of most fields using coupled systems is overall closer to observational data; however, some fields can be degraded as strong sensitivities to the configuration of the individual components still exists. Wiese et al. (2019) showed that significant wave height was depicted very well until the significant wave height reached 6 m in their coupled simulation, while larger significant wave heights tended to be underestimated. Lewis et al. (2019b) found that the fully coupled version of the UKC3 showed a larger bias in the wave related fields relative to the ocean–wave system, with no clear improvement or even degradation in performance across the experiments. Hence, they identified that further analysis was necessary to examine temporal periods such as storm events during which model performance was particularly degraded.

More detailed assessment of the coupled and uncoupled systems, focused on the wave model performance, will allow an identification of the strengths and weaknesses in each, highlighting the points that may need further development in order to be improved. Following Lewis et al. (2019a,b) a comprehensive assessment of the effect of the different levels of coupling in the wave and wind fields relative to the wave only set-up is performed. This work analyses the role of coupling between surface wave, ocean and atmospheric models on the wind and wave fields across the northwest European continental shelf (herein NWS) during an exceptional period of extreme events, when differences in models using different levels of coupling are expected to be the greatest (e.g., Wiese et al., 2019). The report is structured as follows. A brief description of the UKC4 model configuration is detailed in Section 2. The methodology followed for the assessment of the different levels of coupling (including experiments specifications) is shown in Section 3. Experiments validation and model skill are presented in Section 4, and model performance considering only the storms is detailed in Section 5. Finally, the effect of the different levels of coupling on the wave and wind fields is discussed in Section 6. Some conclusions are enumerated in Section 7.

2. Regional Met Office UKC4 model

The UK regional model (UKC4) covers seas on the northwest European continental shelf (approx. 46N-63N, 19W-13E; Fig. 1) and is based on a rotated pole coordinate system with origin in longitude 177.5 degrees and latitude 37.5 degrees. Model components of the UKC4 system are: (i) atmosphere with Met Office Unified Model (UM; e.g., Brown et al., 2012); (ii) ocean using Nucleus for European Models of the Ocean (NEMO ocean model; Madec et al., 2016); and (iii) surface waves component using WAVEWATCH III (Tolman, 2014).

2.1. Met Office Unified atmosphere model

The atmosphere component of the UKC4 consists of the Met Office Unified Model (UM). This convection-resolving model at version 11.1 (e.g., Brown et al., 2012) incorporates the Joint UK Land Environment Simulator land surface model (JULES, version 5.2; Best et al., 2011; Clark et al., 2011). In common with the other UKC4 system components, the atmosphere model domain covers the northwest European region. The grid has variable resolution stretching from 0.036 (~4 km) to 0.0135 (~1.5 km; inner domain covering UK and Ireland) and uses 70 vertical levels (model top ~40 km). The horizontal discretization of this regular grid follows Arakawa C-grid staggering (Arakawa and Lamb, 1977) and the vertical discretization uses Charney–Phillips (Charney and Phillips, 1953). The surface drag coefficient is tuned for the land part of the domain and the atmospheric model grid resolution is sufficient that convection is explicitly represented rather than parameterized. Assessment of features at this resolution can be prone to double penalty effects - physics more realistic but not in the right place and timestep. See Lewis et al. (2019b) for a detailed description of the UM configuration.

2.2. NEMO ocean model

The ocean component of the UKC4 uses the NEMO ocean model (Madec et al., 2016) at version 3.6. The model domain has 1.5 km horizontal resolution matching where overlapping with the inner UM domain. The vertical grid uses 51 hybrid z*-s levels (Siddorn and Furner, 2013). The model uses a non-linear free surface, an energy conserving form of the momentum advection, and a free slip lateral momentum boundary condition (Tonani, 2019). Turbulent viscosities and diffusivities are computed using the generic length scale scheme by Umlauf and Burchard (2003). The tracer equation follows a TVD (Total Variance Diminishing) advection scheme (Zalesak, 1979).

When not coupled to the atmosphere, meteorological forcing in UKC4 is applied using direct forcing by atmosphere–model winds and radiative fluxes. Tides are determined using 15 tidal constituents and included both on the open boundary conditions via a Flather radiation boundary condition (Flather, 1976) and through the inclusion of the equilibrium tide.

2.3. WWIII spectral wave model

The wave model is based on the WAVEWATCH III spectral model (Tolman, 2014) version 4.18. Model physics are based on the ST4 package, which uses wave growth and dissipation parameterisations following Ardhuin et al. (2010) and minor tuning adjustments for compatibility with Met Office wind forecast data (Saulter et al., 2017). This switch for source term wind–wave interaction parameterisations is represented by the atmosphere–wave interaction term S_{in}, nonlinear wave–wave interactions term S_{nl} and a wave–ocean interaction term that is generally dominated by wave breaking S_{ds}. Shallow water dissipation of wave energy uses the surf breaking parameterisation proposed by Battjes and Janssen (1978) and JONSWAP bottom friction. No routine is used for flux computation as this is included in the source terms. Additionally, a switch to enable linear wave growth (LN1; Cavaleri and Malanotte-Rizzoli, 1981) for lower winds is also implemented.

The UK wave model is based on a two-tier Spherical Multiple-Cell grid refinement (Li, 2011) where the coarsest (open waters) cells are resolved at approximately 3 km and coastal cells with water depth less than 40 m are resolved at 1.5 km. The configuration is named as AMM15SL2, denoting its derivation from the AMM15 ocean model configuration for the same region and use of two SMC levels (Saulter et al., 2017). Refer to Saulter et al. (2016) for a detailed description of the wave model configuration.

3. Methods

UK regional model (1.5 km regular grid with 3–1.5 km SMC grid) performance during extreme events is analysed using different levels of coupled exchanges: ocean–wave (forced by atmosphere) and atmosphere–ocean–wave. These are then compared against wave only model runs (wave with wind forcing only, and wave forced with both wind and currents). Model runs extended from 2013-11-01 to 2014-03-03 and the verification comprises the entire run period except for the first 5 days during which the model spins-up (2013-11-06 to 2014-03-03). This set of model runs encompasses the extreme events of 2013/2014 winter, during which the most severe events in the last 60 years hit the Atlantic coast of Europe and the UK (Masselink et al., 2016). Overall, the period from mid-December 2013 to mid-February 2014 saw at least 12 major winter storms.

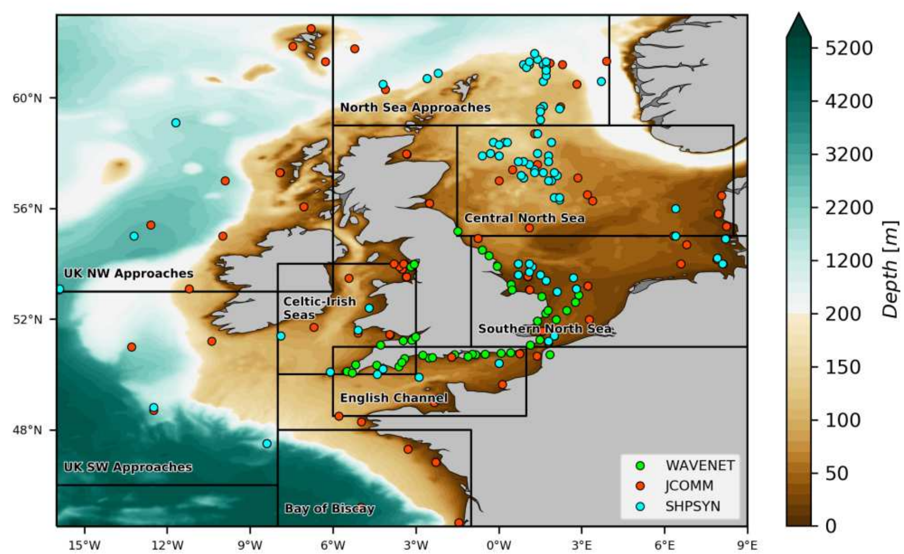

Figure 1 In-situ observations and areas for analysis across the NWS model domain.

3.1 Wave and wind observations for model evaluation

Model experiments are evaluated using in-situ and satellite altimeter wave and wind observations. In-situ data consists of floating buoys and fixed marine platforms. These are comprised by 6-hourly Joint Commission On Marine Meteorology's operational Wave Forecast Verification Scheme observations (Bidlot et al. 2007, hereafter referred to as the

JCOMM-WFVS), hourly Global Telecommunications System data from sea based stations (herein SHPSYN), and hourly UK WAVENET coastal observations. The latter only includes measurements of wave statistics. The satellite merged altimeter data (hereinafter MA data) include data from the JASON-2, CryoSat and SARAL-AltiKa missions. The altimeter significant wave heights used here are corrected according to the calibration provided by CERSAT (Queffeulou, 2013). For a more detailed description on the observational datasets refer to Saulter et al. (2018).

3.2 Experiments set-up

Table 1 Experiments specifications.

Configuration	Experiment	Description
Coupled	UKC4aow	Atmosphere-ocean-wave coupling atm <-> ocn <-> wave <-> atm Wave model driven by 1.5 km-scale winds from coupled atmosphere
	UKC4ow	Ocean-wave coupling with global NWP meteorological forcing (including 25-km global winds) from the Met Office Unified Model interpolated to CMEMS- UK MetOffice AMM15 ocn <-> wave
Wave-only	UKW4g	Wave only forced with Met Office NWP 25-km global winds interpolated to CMEMS- UK Met Office AMM15
	UKW4cg	Wave only forced with Met Office NWP 25-km global winds interpolated to CMEMS- UK Met Office AMM15 and currents from CMEMS- UK Met Office AMM15
	UKW4h	Wave only forced with Met Office ukv high-resolution winds (4–1.5km) interpolated to CMEMS- UK Met Office AMM15

Atmosphere-ocean-wave; UKC4aow

The fully coupled atmosphere–ocean–wave configuration for the NW European Shelf, herein UKC4aow, uses two-way feedbacks between all model components within the system (Lewis et al., 2019b). Exchange of information between NEMO, WWIII and UM is achieved using Ocean Atmosphere Sea Ice Soil coupling libraries version 3.0 (OASIS-MCT coupler; Valcke et al., 2015).

Table 2 lists the coupling exchanges relevant to the wave field modelling in the fully coupled system. All coupling exchanges in UKC4aow are:

- 10 m winds (W_s) are passed from the atmospheric model to the wave model, which returns the wave dependent Charnock's coefficient (α) to the atmosphere.
- The wave model receives surface currents (U_{cur}) from the ocean model and passes significant wave height (H_s), mean wave period (T_{01}), the surface Stokes drift (U_s), and the fraction of atmospheric stress to the ocean (*tauoc*).
- Atmosphere-ocean transfers are wind speed at 10-m above the surface, surface heat fluxes (solar and non-solar), rainfall and snowfall rates, evaporation of fresh water

from ocean and mean sea level pressure. The ocean model passes sea surface temperature and surface currents to the atmosphere.

Hence, the wave feedback on the atmosphere momentum budget is the modification of the surface roughness through a Charnock coefficient (α) that directly depends on the sea state. For wave feedbacks on the ocean momentum budget refer to next Section.

Table 2. Coupling exchanges relevant to wave field modelling.

INTERFACE	Exchanged variable
W-A	Wave-dependent Charnock parameter (α)
O-W	Surface current (U_{cur})
W-O	Significant wave height (H_s)
W-O	Stokes drift velocity (U_s)
W-O	Mean wave period (T_{01})
W-O	Wave to ocean energy flux (*tauoc*)
A-W	Wind speed at 10 m above surface (W_s)

Ocean-wave; UKC4ow

The ocean–wave coupled experiment, herein UKC4ow, includes two-way feedbacks between ocean and wave components. Similar to the UKC4aow experiment, the exchange of information between the 1.5 km eddy-resolving Atlantic Margin Model (AMM15) ocean NEMO model and the WWIII model is achieved using the OASIS-MCT coupler (Valcke et al., 2015). This partially coupled experiment follows a direct forcing approach with meteorological forcing provided from external files by the global Met Office Unified Model (running at order 25 km resolution for the time of this study) and interpolated to the AMM15 grid. The wave feedbacks on the ocean momentum budget include parameterisations for the Stokes-Coriolis force (see Section 3.3 in Lewis et al., 2019b), modified wind stress by wave growth and dissipation (Breivik et al., 2015; see Section 3.2 in Lewis et al., 2019b), and wave height dependant sea surface roughness (Rascle et al., 2008; see Section 3.4 in Lewis et al., 2019b).

Wave only; UKW4g, UKW4h and UKW4cg

Wave only model runs are used as control simulations. This set of uncoupled model runs do not include feedbacks with external model components; only hourly wind and/or current forcing read from external files. All waves standalone experiments use the same wave model set-up and tuning parameters; however, experiments were not run using the same suites, differing mainly in the pre-processing routines (i.e., external forcing interpolation routines). Hence, this set of waves standalone experiments can be subdivided in two: wind only experiments run using the research suite (UKW4g and UKW4h) and single experiment run using the actual Met Office operational wave model set-up (wind and currents as forcing; UKW4cg). UKW4cg is forced by hourly Met Office 25-km global winds and currents from CMEMS-UK Met Office AMM15. Following the same naming convention, UKW4g and UKW4h experiments are forced by the Met Office 25-km global winds and the hourly UKV high resolution winds (4–1.5km resolution), respectively. Although all forcing fields are interpolated to the CMEMS- UK Met Office AMM15 grid and read as external files, wind forcing in UKW4g and UKW4h are generated using the ocean model pre-processing routine whereas in UKW4cg wind and currents are interpolated using an operational wave pre-processing routine.

3.3 Simulated storms: winter 2013/2014

The severe winter of 2013/2014 is considered the most energetic period in terms of storminess in the last 60 years for the Ireland-UK domain (Matthews et al., 2014; Masselink et al., 2016). Overall, mid-December 2013 to mid-February 2014 saw at least 12 major winter storms (Table 3 and Fig. 2). This series of storms represent an exceptional period to study how well different levels of coupling represent the tail of the distribution of the wave field, where wave models traditionally struggle the most. Differences between the individual windstorms in severity and storm track (Table 3) allows analysis of the effect of wave–wind interaction in different areas of the NW shelf. Two particular storms affecting the UK shelf seas are highlighted: storm Xaver and Ruth (Fig. 2a-j and Table 3). The former generated a major storm surge affecting North Sea and the coast of North Wales, Scotland and northern England. Gusts exceeded 60 kt along North Sea and Irish Sea coasts and over 70 kt in the Western Isles. Storm Ruth affected the Irish and Celtic Seas with winds gusting at 60 to 70 kt around the coastline of South Wales and SW England.

Table 3 Main characteristics of the extreme windstorms during winter 2013/2014.

DATE	P_{min} (hPa)	LOCATION	COMMENTS
5 – 6 Dec 2013	962	North Sea and Irish Sea	Named 'Xaver'. Major storm surge affecting North Sea coasts and North Wales. Scotland and northern England. Gusts exceeded 60 kt along North Sea and Irish Sea coasts and over 70 kt in the Western Isles.
18 – 19 Dec 2013	941	Western Scotland and Northern Ireland	Named 'Bernd'. Winds gusted widely at 60 to 70 kt around exposed coastlines of the north and west, with gusts exceeding 70 kt in the Western Isles, South Wales and South Coast.
23 – 24 Dec 2013	927	South coast of England and Welsh Coastline (NW)	Named 'Dirk'. High spring tides and large waves combining to cause an extreme risk of coastal flooding. Winds gusted at 60 to 70 kt across much of Scotland, the coast of Wales and South Coast of England.
26 – 27 Dec 2013	945	South coast of England and Welsh Coastline (NW)	Named 'Erich'. High spring tides and large waves combining to cause an extreme risk of coastal flooding. Winds again gusted widely at 50 to 60 kt, with the strongest winds around Irish Sea coast.
3 Jan 2014	934	SW England and South Wales	Named 'Christina'. Winds gusted at 60 to 70 kt around exposed coastlines of the south and west.
5 Jan 2014	949?	SW England and South Wales	Named 'Hercules'. Low pressure in the north Atlantic, driving strong winds and coinciding with high spring tides resulted in exceptionally high waves affecting the South Coast of England and west coast of Wales.
25 – 26 Jan 2014		More severe in North and West UK	This individual storm was notable but not exceptional. Winds gusted widely at 50 to 60 kt around exposed coastlines of the west and north UK.
31 Jan – 01 Feb 2014	945	More severe in North and West UK	This individual storm was notable but not exceptional. Winds gusted widely at 50 to 60 kt around exposed coastlines of the north and west UK.
04 – 05 Feb 2014	950	South Wales and SW England	Named 'Petra'. This storm was more severe than the previous two, particularly across south Wales and south-west England where winds gusted at 60 to 70 kt widely around exposed coastlines.
08 – 09 Feb 2014	945	South Wales and SW England	Named 'Ruth'. Wind speeds were comparable with the previous storm and again gusted at 60 to 70 kt around the coastline of south Wales and south-west England.
12 – 13 Feb 2014	960	Wales and NW England	Named 'Tini'. This storm was arguably the most severe of the sequence, particularly for coastal areas of Wales and north-west England where winds gusted at 70 to 80 kt.
14 – 15 Feb 2014	960	S Wales and S England	Named 'Ulla or Valentine's Day'. The coasts of south Wales and southern England were affected by the strongest winds, gusting at 60 to 70 kt or higher.

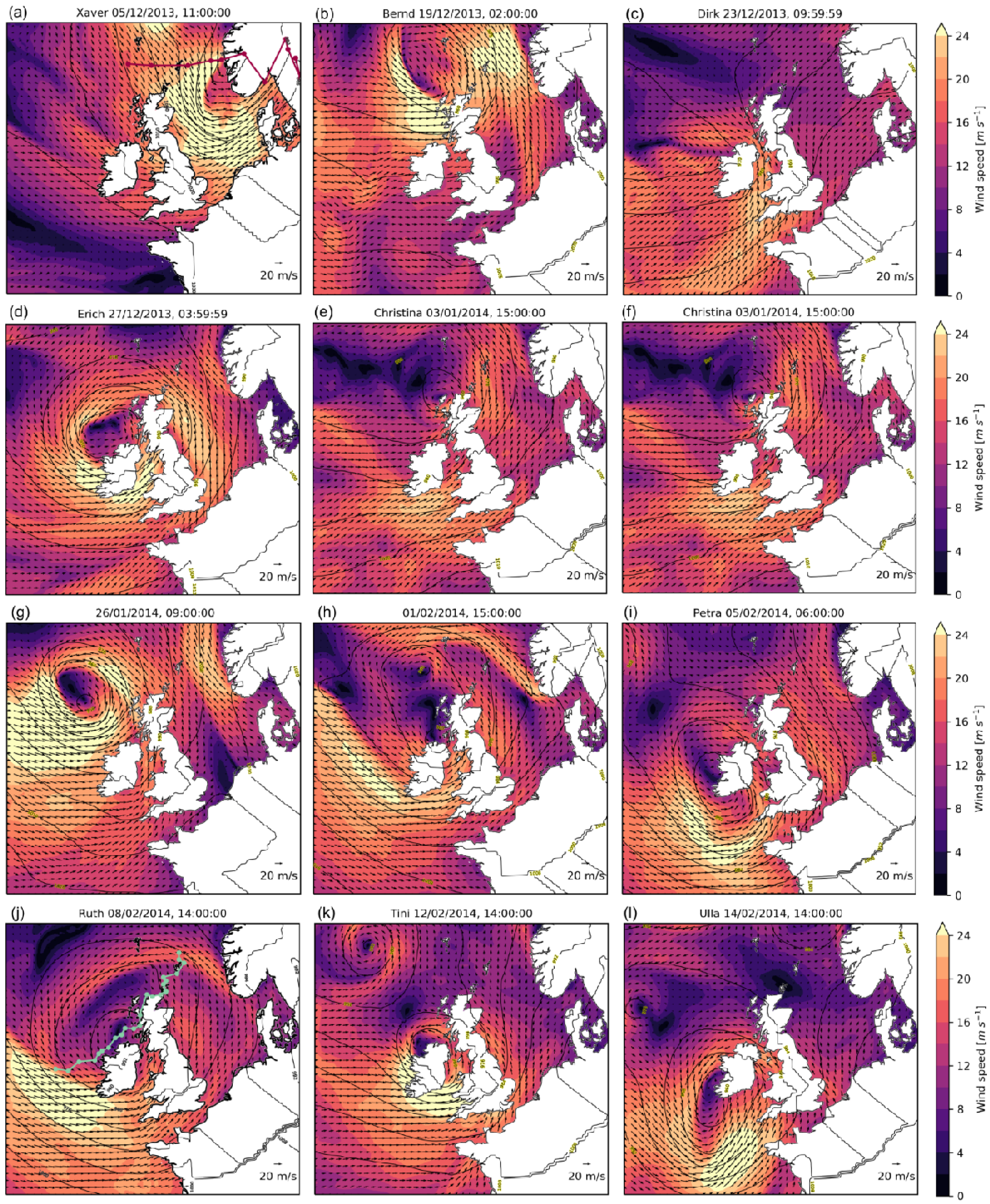

Figure 2 Snapshots of the most severe extreme windstorms during winter 2013/2014. Each individual storm snapshot includes wind speed, wind direction vectors and mean sea level pressure contours. Storm tracks of storm Xaver (a) and storm Ruth (j) are also included. Winds are extracted as sea points only from WWIII system component - UKC4ow experiment. To facilitate visualization, wind vectors are plotted every 35 grid points. Pressure contours are sourced from the global pressure forcing conditions.

4. Model validation

UKC4aow, UKC4ow and wave only (UKW4#) experiments are compared against WAVENET, JCOMM-WFVS, SHPSYN and MA observations, and summary statistics for significant wave height (H_s), peak period (T_p) and wind speed (W_s) are presented in Table 4. Overall, the main results are: (i) UKC4ow shows the best skill score of the research suite hindcasts, yielding a small improvement over the waves standalone research configuration UKW4g; (ii) hindcasts forced by the global atmosphere data (UKC4ow, UKW4cg, UKW4g) clearly perform better than the experiments using the high resolution atmosphere (UKC4aow, UKW4h); (iii) performance of the fully coupled run UKC4aow is substantially improved relative to the uncoupled high resolution atmosphere forced standalone wave experiment UKW4h, for all in-situ observations. ; and (iv) the best overall performance is from the current operational configuration UKW4cg, with disagreements between UKC4ow, UKW4g and UKW4cg results believed to be mainly associated to differences between the research and operational suite pre-processing methods.

Fig. 3, 4 and 5 show regional changes in skill comparison between atmosphere–ocean–wave coupled experiment (UKC4aow), ocean–wave coupled experiment (UKC4ow) and wave only (UKW4g). Wave–current interaction in areas such as the English Channel and Bideford Bay leads to larger variability in wave height and changes in the wave period, due to a range of processes that are not represented in the wave standalone experiments. It is in these areas with important tidal modulation that the absence of effects due to changing tidal currents and elevations may limit the accuracy of the wave model (not shown; refer to Palmer and Saulter, 2016). Overall the figures show that the coupled systems introduce both benefits and detriments to wave forecast performance. The most consistent results are that UKC4ow presents a better skill score in coastal areas where the tidal currents are significant such as the English (Fig. 3) and Bristol Channels (Fig. 4). Conversely, T_p error changes increase when including the currents as forcing in some offshore areas such as North Sea approaches and UK NW approaches (Fig. 5). Overall, it is noted that model skill of UKC4ow and UKW4g is very similar. UKC4aow presents an improvement of 2–3% in skill score for H_s at some of the WAVENET coastal locations (e.g., Liverpool Bay and Bristol Channel Approaches; Fig. 4). It should be highlighted the degradation of model skill for H_s for UKC4aow and UKC4ow experiments across the North Sea (> 5%; Fig. 3) with a consistent underestimation of observations for H_s > 3.5 m that is less evident in the wave-only experiments (Fig. 7).

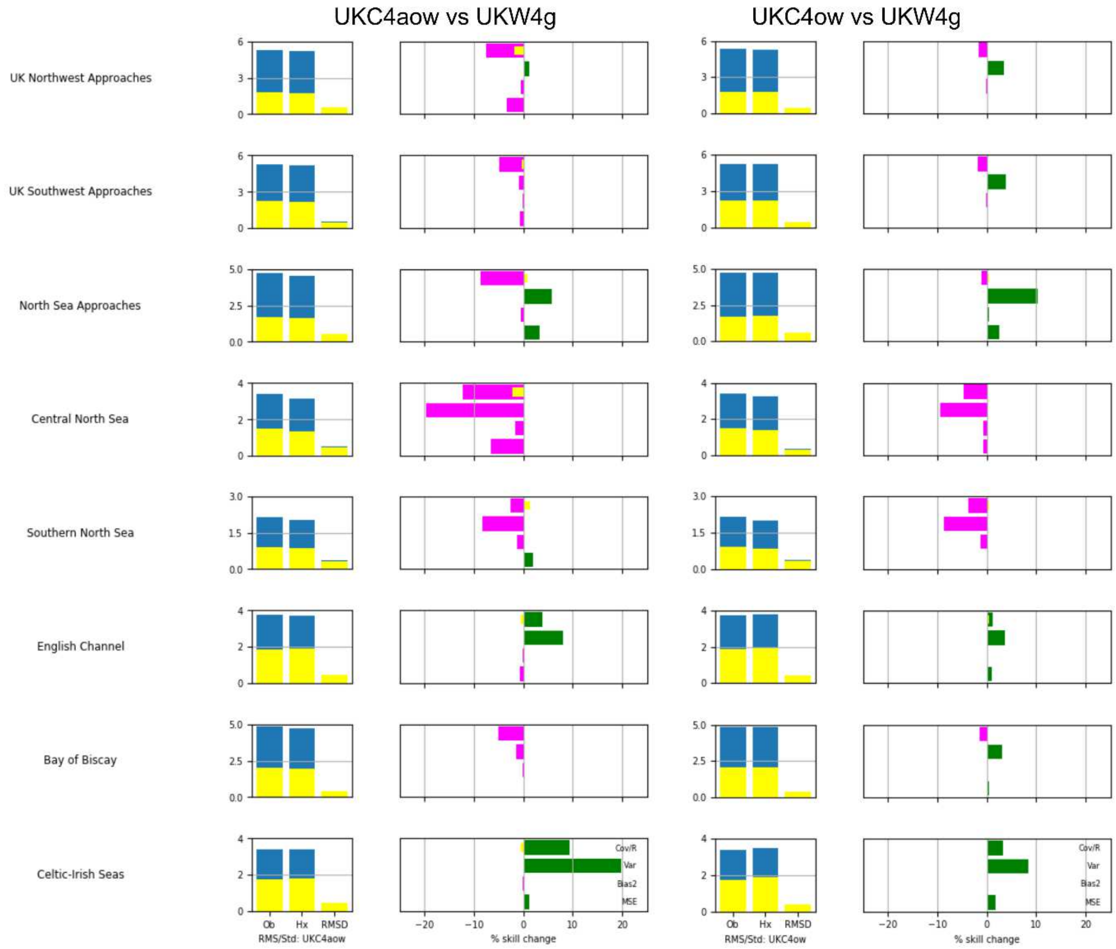

Figure 3 Merged altimeter (MA) observations-model comparison and error changes of significant wave height (H_s) for UKC4aow-UKW4g (left panels) and UKC4ow-UKW4g (right panels). Magenta (decrease of skill score) and green (increase of skill score) bars represent percent of skill change of UKC4aow and UKC4ow with respect to UKW4g. Refer to Fig. 1 for area extent.

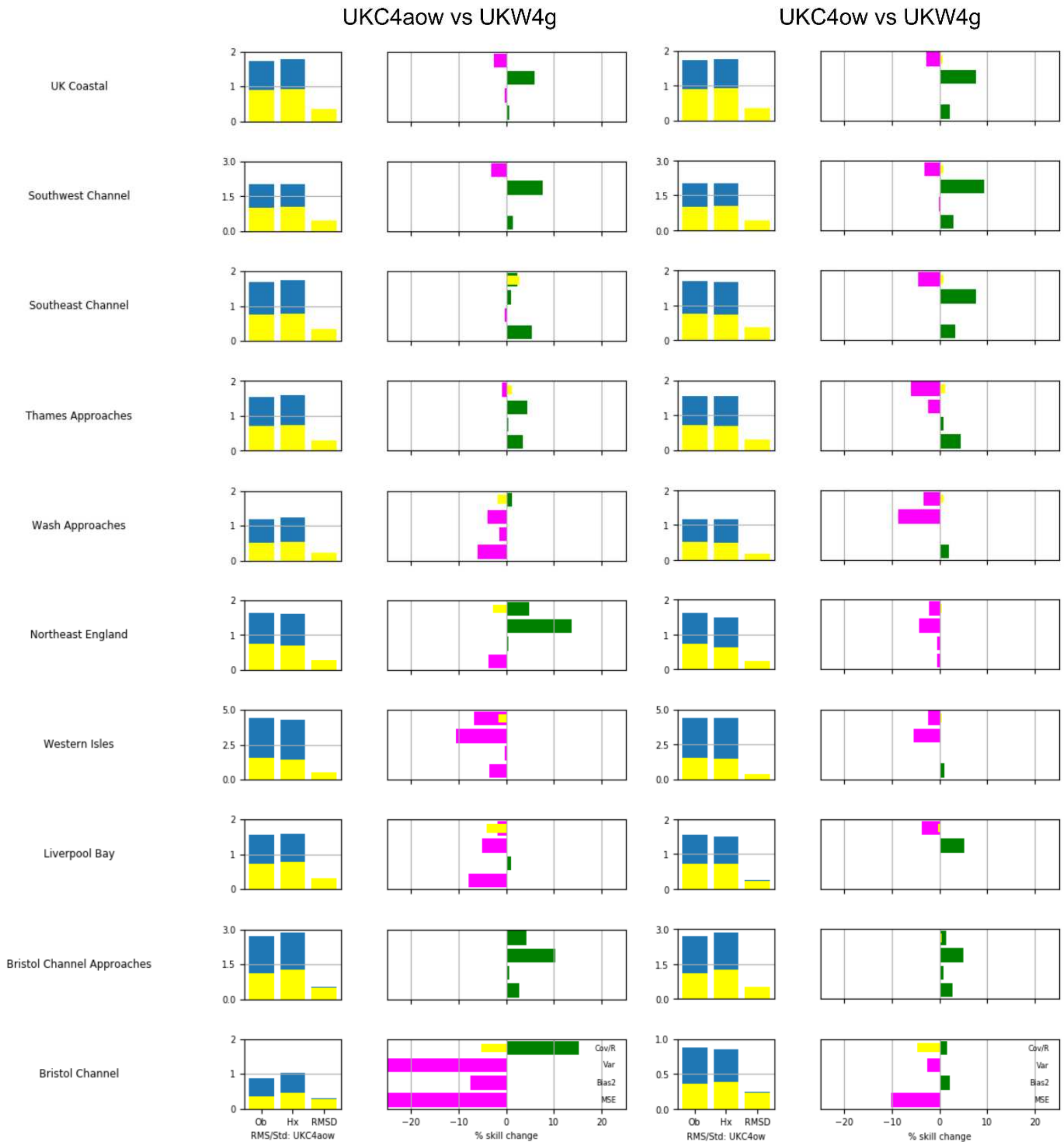

Figure 4 WAVENET coastal in-situ observations-model comparison and error changes of significant wave height (H_s) for UKC4aow-UKC4g (left panels) and UKC4ow-UKW4g (right panels). Magenta (decrease of skill score) and green (increase of skill score) bars represent percent of skill change of UKC4aow and UKC4ow with respect to UKW4g. Refer to Fig. 1 for area extent.

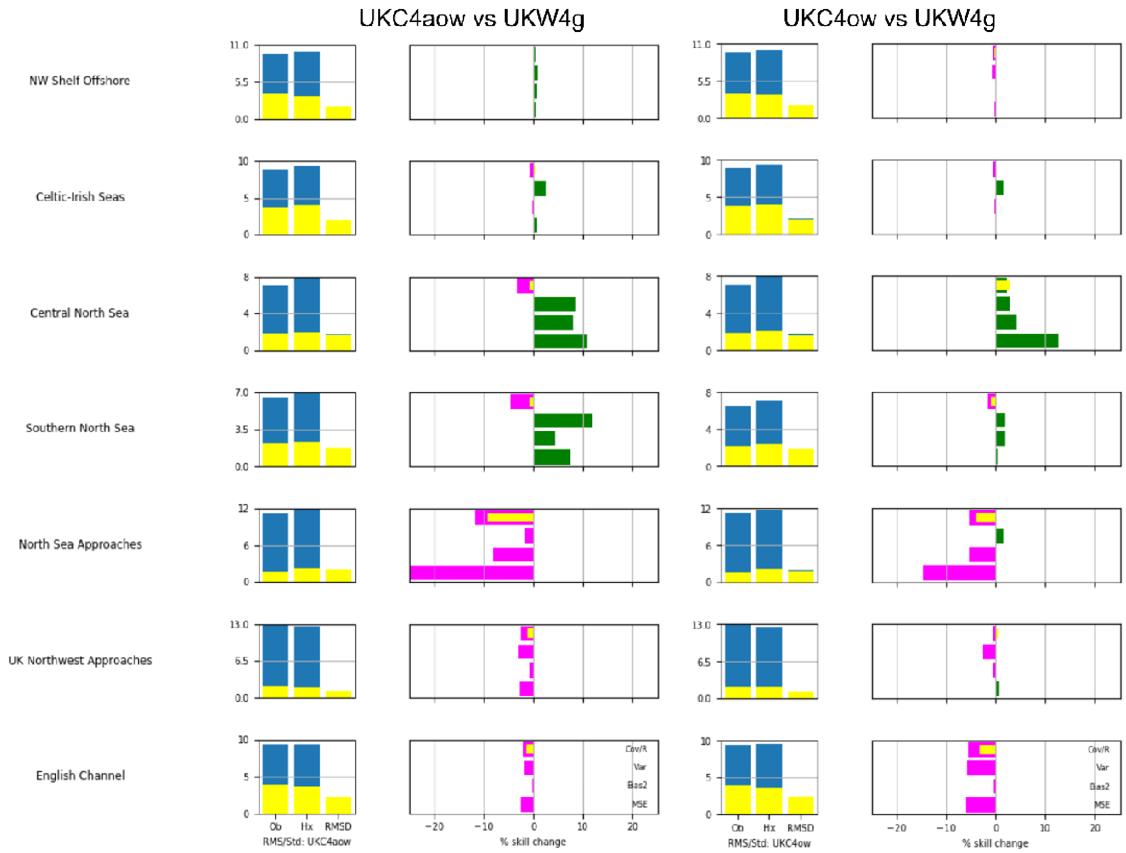

Figure 5 JCOMM WFVS in-situ observations-model comparison and error changes of peak period (T_p) for UKC4aow-UKC4g (left panels) and UKC4ow-UKW4g (right panels). Magenta (decrease of skill score) and green (increase of skill score) bars represent percent of skill change of UKC4aow and UKC4ow with respect to UKW4g. Refer to Fig. 1 for area extent.

Atmosphere–ocean–wave coupling (UKC4aow) uses UKV high-resolution winds (4km to 1.5km) whereas ocean–wave and waves standalone UKW4g uses 25-km global winds from external files. Both winds show negative bias with respect to observed altimeter winds (Table 4; bias = -1.276 m s^{-1} and -1.02 m s^{-1} for UKC4aow and UKC4ow, respectively); however the coarser resolution atmosphere presents a better agreement with the observations (RMSD = 1.937 m s^{-1} and R=0.932 respect RMSD = 2.51 m s^{-1} and R=0.876 for high-resolution winds). Furthermore, the decrease in skill change for H_s showed by UKC4aow is even greater when we compare W_s (both UKC4aow and UKW4h), where MSE increases between 20 to 5% in all the locations (Fig. 6). It could be argued that the higher resolution in the wind forcing appears to degrade the other diagnostic variables. A comparison between UKW4h and UKW4g (i.e., high resolution versus global winds; Fig. 6-right panels) suggests that this degradation in W_s is in fact more related to a regional/ high resolution feature than driven directly by the coupling to the other components.

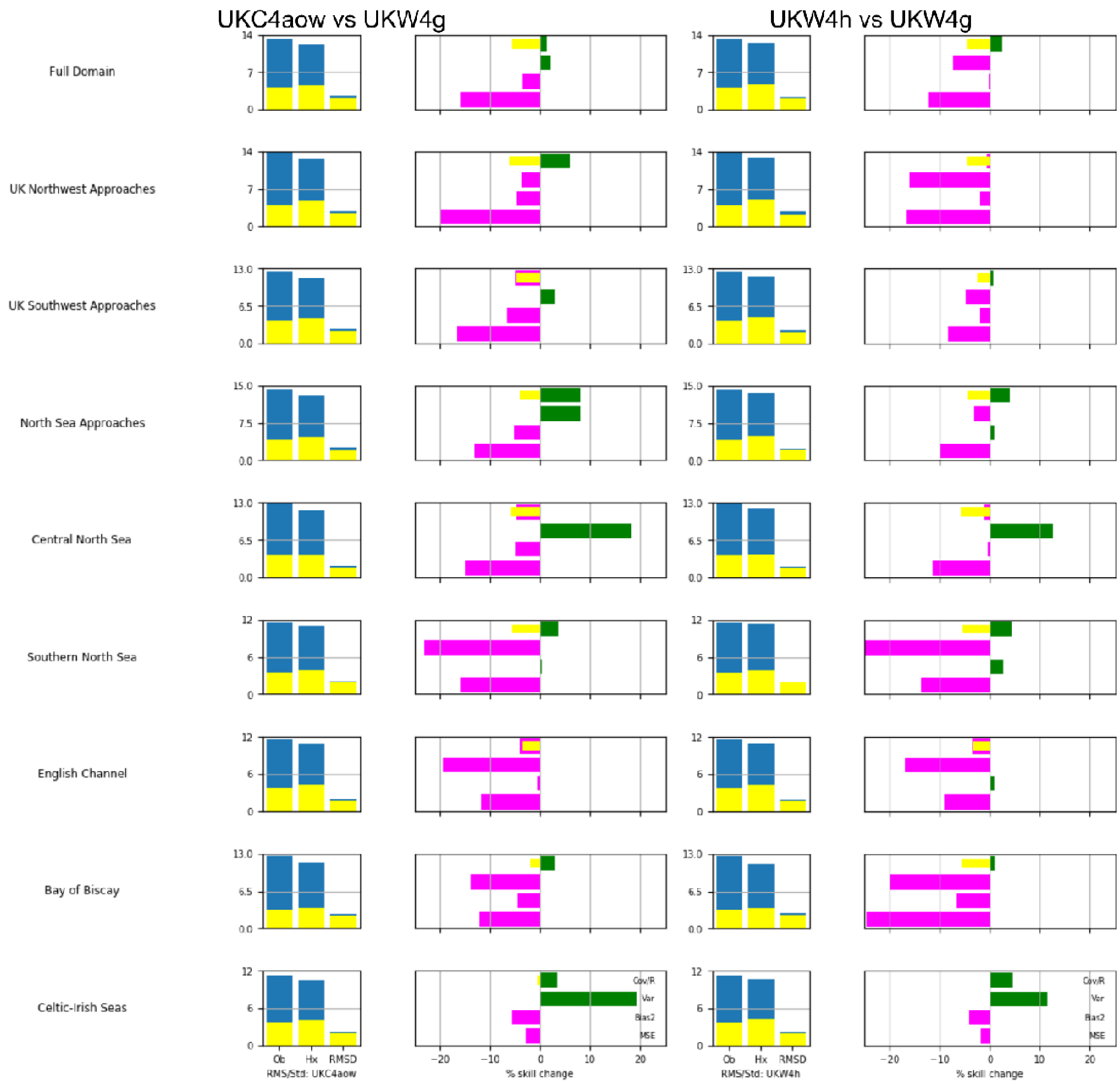

Figure 6 Merged altimeter (MA) observations-model comparison and error changes of wind speed (W_s) for UKC4aow-UKW4g (left panels) and UKW4h-UKW4g (right panels). Magenta (decrease of skill score) and green (increase of skill score) bars represent percent of skill change of UKC4aow and UKW4h respect UKW4g. Refer to Fig. 1 for area extent.

QQ and scatter plots for H_s for the full domain (top panels), the North Sea (mid panels) and the UK coastal locations (bottom panels) are presented in Fig. 7. Despite that all experiments (UKC4aow, UKC4ow and UKW4g) present an average negative bias for the full domain, UKC4aow bias is significantly larger (bias = -0.12 m with respect to -0.058 m and -0.004 m for the global atmosphere forced runs). In particular, UKC4aow underestimates observations in the upper tail of H_s (beyond 8 m). It is indeed in the North Sea where the largest differences between the experiments are observed: (i) UKC4aow significantly underestimates between 4 to 10 m height with biases close to -2 m for waves of 6 m height;

and (ii) UKC4ow shows the best hindcast of large waves and this is very similar to UKW4g. UKC4ow better reproduces observations in the coastal locations and differences in skill score between UKC4aow and the former are reduced respect open water observations. All models overpredict for waves beyond 3.5 m in coastal waters. This overestimation is smoothed out in the UKC4ow and UKC4aow, where overestimation of high-energy to extreme events is still observed but is smaller.

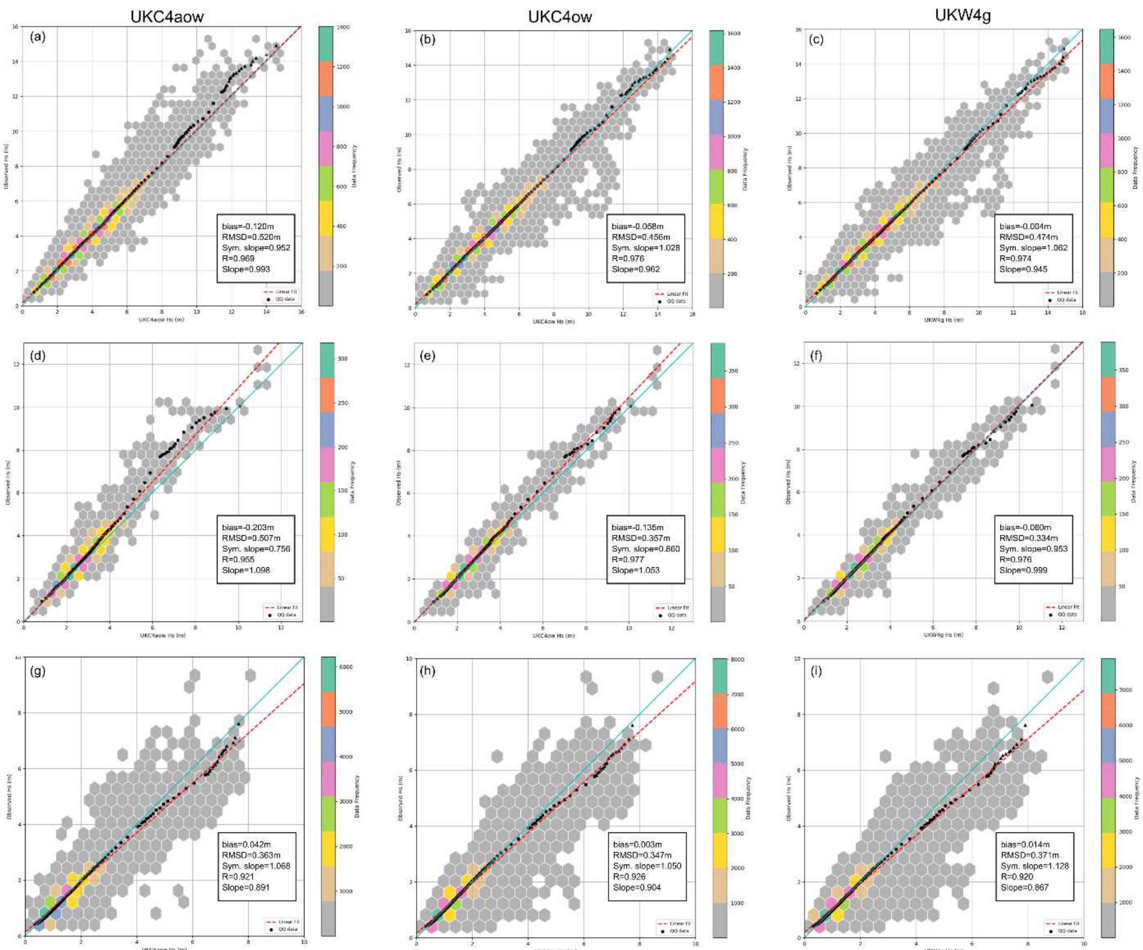

Figure 7 Significant wave height (H_s) QQ and scatter data for merged altimeter observations for the full domain (a-c), for the Central North Sea (d-f) and WAVENET UK coastal in-situ observations (g-i). Observations are compared against model hindcast from the UKC4aow (a,d,g), UKC4ow (b,e,h) and UKW4g (c,f,i). Refer to Fig. 1 for area extent and location of in-situ observations**.**

Table 4 Summary statistics for significant wave height (H_s), peak period (T_p) and wind speed (W_s): UKC4aow, UKC4ow, UKW4g and UKW4h versus observations of merged altimeter (MA), WFVS, SHPSYN and WAVENET over 20131106 to 20140303.

Var.	Obs.	RMSD					Bias					R				
		UKC4aow	UKC4ow	UKW4g	UKW4cg	UKW4h	UKC4aow	UKC4ow	UKW4g	UKW4cg	UKW4h	UKC4aow	UKC4ow	UKW4g	UKW4cg	UKW4h
H_s	MA	**0.52**	0.456	0.474	**0.398**	**0.53**	**-0.12**	-0.058	-0.004	**-0.044**	**0.021**	0.969	0.976	0.974	0.982	0.967
	WFVS	**0.474**	0.439	0.472	**0.406**	**0.539**	**0.019**	0.037	0.095	**0.053**	**0.153**	0.966	0.971	0.969	0.976	0.962
	WAVENET	**0.335**	0.306	0.321	**0.286**	**0.358**	**0.017**	-0.027	-0.015	**-0.015**	**0.057**	0.949	0.957	0.955	0.963	0.947
	SHPSYN	**0.541**	0.493	0.524	**--**	**0.608**	**0.028**	0.055	0.117	**--**	**0.171**	0.954	0.962	0.96	--	0.948
T_p	WFVS	1.837	1.852	1.845	1.860	1.916	0.226	0.334	0.349	0.355	0.303	0.865	0.865	0.867	0.864	0.855
	WAVENET	2.597	2.655	2.643	2.639	2.624	0.411	0.557	0.481	0.566	0.435	0.754	0.749	0.75	0.753	0.753
	SHPSYN	3.342	3.407	3.382	--	3.378	1.742	1.814	1.842	--	1.839	0.54	0.537	0.55	--	0.546
W_s	MA	2.51	1.937	1.937	1.937	2.401	-1.276	-1.02	-1.02	-1.02	-1.034	0.876	0.932	0.932	0.932	0.885
	WFVS	2.256	1.823	1.823	1.823	2.306	0.635	0.454	0.454	0.454	0.871	0.878	0.922	0.922	0.922	0.889
	SHPSYN	2.597	2.219	2.219	--	2.659	0.561	0.604	0.604	--	0.841	0.843	0.89	0.89	--	0.85

5. Models performance during the storms

Average values of the main diagnostic variables used to analyse the performance of the different degrees of coupling during the storms are presented in Fig. 8. Distribution of fields such as mean significant wave height (H_s), wave modified surface drag coefficient (C_d), or wave-supported wind stress (τ_{aw}) help to interpret the sensitivity in storms.

For H_s (Fig. 8a), the largest mean values are observed in the W-WSW part of the domain, indicating the prevailing track of the storms as a consequence of the jet stream. The southern part of the North Sea together with the coastal zones on the east coasts of Ireland and the UK are the least energetic areas with average heights of 2.5 m. This gradient in H_s is mainly controlled by the combination of bathymetry, orography, wind distribution and fetch (Fig. 8d). Regarding the normalised stress fraction to the ocean (normalised stress *tauoc*; Fig. 8f), the largest absorption rates can be found along exposed west-facing coastlines, and major reductions are found in the lee of land such as downstream of the Scottish islands, in the Irish Sea and along the English Channel. As expected, wind stress, Charnock and drag coefficient follow the same distribution as the 10 m above the surface wind speed. Largest values of these fields are observed in the W of the domain and the E part of the shelf break in the North Sea (Fig. 8b,c,e), not always corresponding with the largest waves (Fig. 8a) but consistent with regions of wind-sea development; whereas the smallest mean values for this stormy period are consistently located at the north of NW approaches.

Model skill score is evaluated for the period of "only storm". In this case we define a storm period when $H_s > H_{s,75\%}$ (Q75%); however, in order to analyse performance during the extremes, $H_s > H_{s,90\%}$ criteria (Q90%) is also used for the analysis. When analysing model performance reproducing the upper tail of the distribution, three major features are repeated:

i. all models tend to overpredict H_s during the storms in the sheltered coastal locations;
ii. the atmosphere–ocean–wave coupled model appears to underestimate substantially the fast storm growth on the continental shelf, and the peak of the storm is also underestimated during the storms; and
iii. wave–only forced by MO global winds and ocean–wave coupled shows the best skill score reproducing the fields during the storms in the continental shelf, and this is very similar for both models.

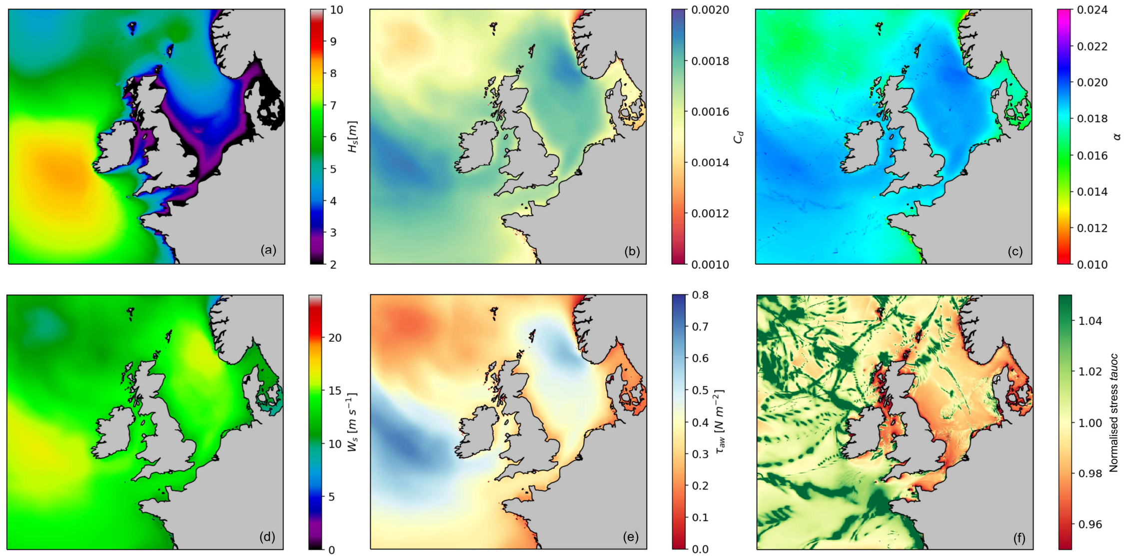

Figure 8 (a) Distribution of mean significant wave height (H_s), (b) wave modified surface drag coefficient (C_d), (c) Charnock coefficient (α), (d) wind speed (W_s), (e) wave-supported wind stress (τ_{aw}) and (f) stress fraction to the ocean (normalised stress *tauoc*) computed using the wave-only configuration (UKW4g) for the period of storms.

During the storms, the largest differences between the different levels of coupling are observed on the shelf (Fig. 9 and Table 5). Similar to the model performance during the four months of hindcast, both UKC4ow and UKW4g present the best skill score when simulating large waves (Table 5) with some subtle differences. UKC4ow seems to underestimate more than UKW4g the upper tail on the shelf (North Sea mainly), except for the most extreme events (c. H_s = 10 m; Fig. 7d), during which the latter appears to underpredict less (see also average negative differences between UKC4ow and UKW4g, Fig. 10). UKC4aow presents poorer performance with weaker agreement to observations (R=0.72–0.81; Table 5) when comparing with the other experiments (R=0.75–0.87; Table 5). Furthermore, all models consistently underpredict the waves during the storms; contrarily, UKW4h slightly overestimates these waves off the shelf (exceeding Q75 and Q90; Table 5).

Regarding W_s (Fig. 9g-l), all experiments except for UKW4h follow the same pattern with positive bias off-shelf and negative on-shelf for Q90%. It is noted that this pattern is likely to be platform dependent and results should be treated with caution. Hence, skill score is variable in all models and there is no clear best performance. UKC4aow tends to underestimate on-shelf (bias = -0.181 m s^{-1} and -0.566 m s^{-1} for Q75% and Q90%, respectively) and presents the smallest W_s off-shelf bias during the extremes (0.890 m s^{-1} for Q90%); however, correlation coefficient is poorer (mean R=0.68) than those shown by the other experiments (mean R=0.78).

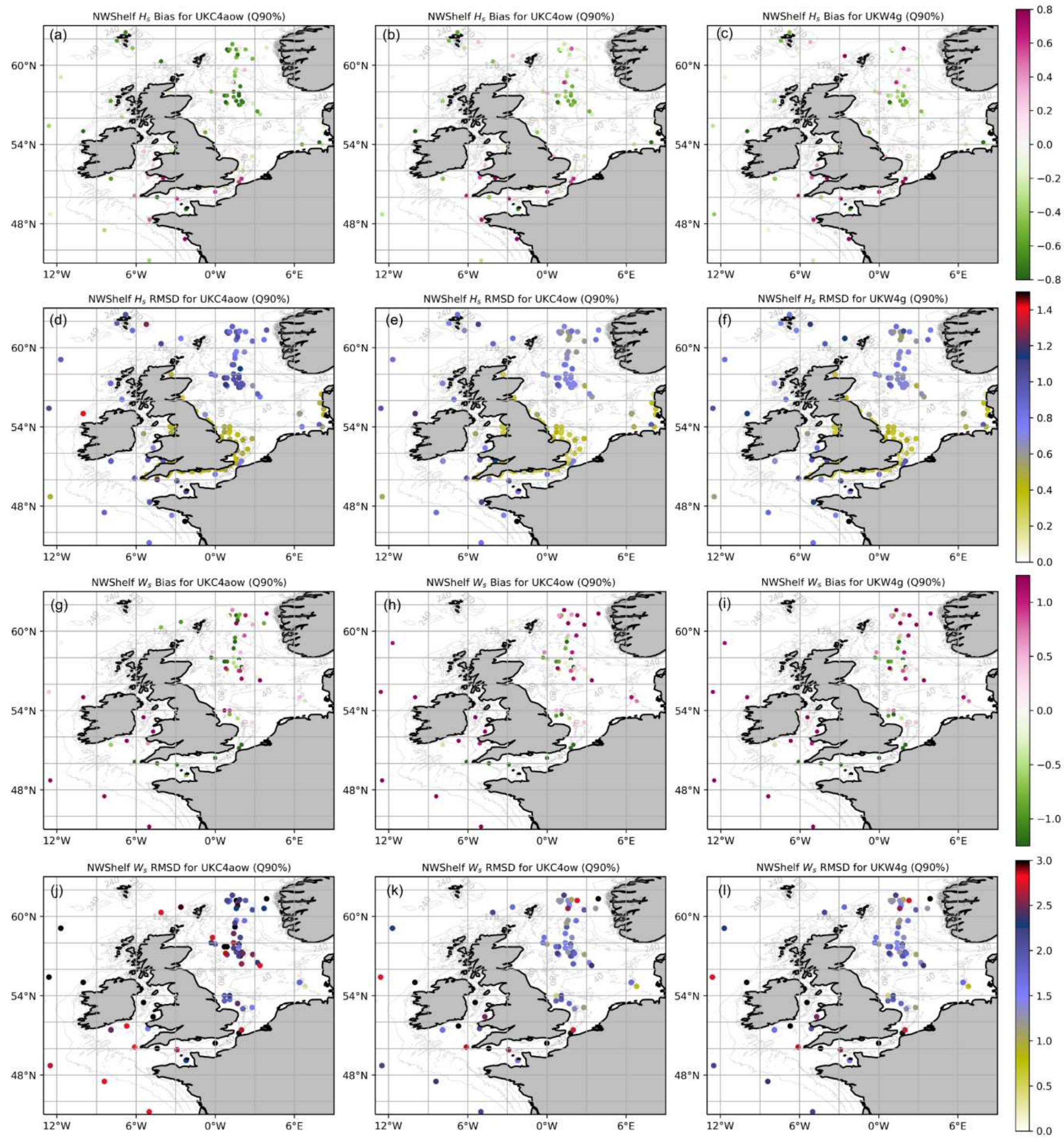

Figure 9 Averaged significant wave height (H_s) and wind speed (W_s) bias (a-c and g-i, respectively) and RMSE (d-f and j-l) for the quantile of 90% at in-situ locations for UKC4aow, UKC4ow and UKW4g.

Table 5 Summary statistics for significant wave height (*H_s*) and wind speed (*W_s*) for the extreme events: exceedance of 75% and 90%. Experiments UKC4aow, UKC4ow, UKW4g and UKW4h are compared against WFVS, SHPSYN and WAVENET observations over 20131106 to 20140303.

Variable	Quantile	Area	RMSE				Bias				R			
			UKC4aow	*UKC4ow*	*UKW4g*	*UKW4h*	*UKC4aow*	*UKC4ow*	*UKW4g*	*UKW4h*	*UKC4aow*	*UKC4ow*	*UKW4g*	*UKW4h*
Hs	Q75	On-shelf	0.971	0.874	0.891	1.001	-0.379	-0.313	-0.237	-0.164	0.814	0.873	0.867	0.808
		Off-shelf	0.843	0.801	0.837	0.918	-0.169	-0.041	-0.046	0.092	0.813	0.829	0.820	0.792
	Q90	On-shelf	1.193	1.058	1.073	1.208	-0.579	-0.463	-0.357	-0.288	0.723	0.807	0.797	0.719
		Off-shelf	0.953	0.880	0.948	1.018	-0.275	-0.124	-0.008	0.046	0.737	0.762	0.749	0.720
Ws	Q75	On-shelf	2.528	2.038	2.038	2.634	-0.181	0.027	0.027	0.167	0.664	0.790	0.790	0.679
		Off-shelf	2.515	2.213	2.213	2.635	0.897	1.194	1.194	1.064	0.717	0.799	0.799	0.730
	Q90	On-shelf	2.698	2.155	2.155	2.773	-0.566	-0.181	-0.181	0.084	0.544	0.723	0.723	0.560
		Off-shelf	2.746	2.378	2.378	2.867	0.890	1.314	1.314	1.162	0.658	0.743	0.743	0.684

6. Role of the different levels of coupling

The mean differences between UKC4aow and UKW4g represent the impact of full atmosphere–ocean–wave coupling relative to a free-running wave–only configuration. Differences are a combination of the impact of a change in meteorological forcing resulting from increased atmospheric resolution from global (25 km) to regional (4 to 1.5 km) scale, ocean–wave interactions and the effect of coupling of momentum across the air–sea interface.

We use two storms (Xaver and Ruth) to describe the pattern in the diagnostic variables wave supported wind stress (τ_{aw}) and Charnock coefficient (α) (Fig. 10 and 11). The largest differences are observed on the continental shelf where, discarding the coastal locations in the lee of the land, the fully coupled experiment shows smaller values of H_s (Fig. 10a and 11a) and slower winds, consistent with the $W_{s,q90\%}$ negative bias on-shelf (*O.*15–19% of the total field; not shown), relative to the control run. H_s differences are more than 1 m on average which corresponds to more than 10% of the average field. Additionally, the wind stress is 0.4 N m^{-2} smaller in the fully coupled experiment in those areas affected most by the storm (North Sea and Irish-Celtic Seas for Xaver and Ruth, respectively; Fig. 10c and 11c). These differences are above 40% of the total signal in some of the mentioned locations. Differences in the pattern of the Charnock coefficient differ from the wind stress and large values of wind stress do not always coincide with large values of Charnock. For storm Xaver, the fully coupled experiment appears to have greater values (with respect to the control run; UKW4g) across the North Sea, while smaller values (negative difference) correspond to areas with both very similar or smaller wind stresses than the control (Fig. 10e). Differences for Charnock across the domain can reach 22% of the total field.

Differences between the ocean–wave coupled experiment and the control run are much smaller in all the fields (c. <2–5% of the field total signal), and these correspond mainly to the lack of ocean currents modulation of the waves in the control run, in particular due to interactions with tidal currents on the shelf and the significant extra 3D structure added by the current modulation off the shelf. On average, the impact of representing ocean–wave feedback processes is shown to be relatively small in comparison with the effect of coupling of momentum across the air–sea interface (c. 2–5% of the field total signal versus 10–40% depending on the diagnostic field).

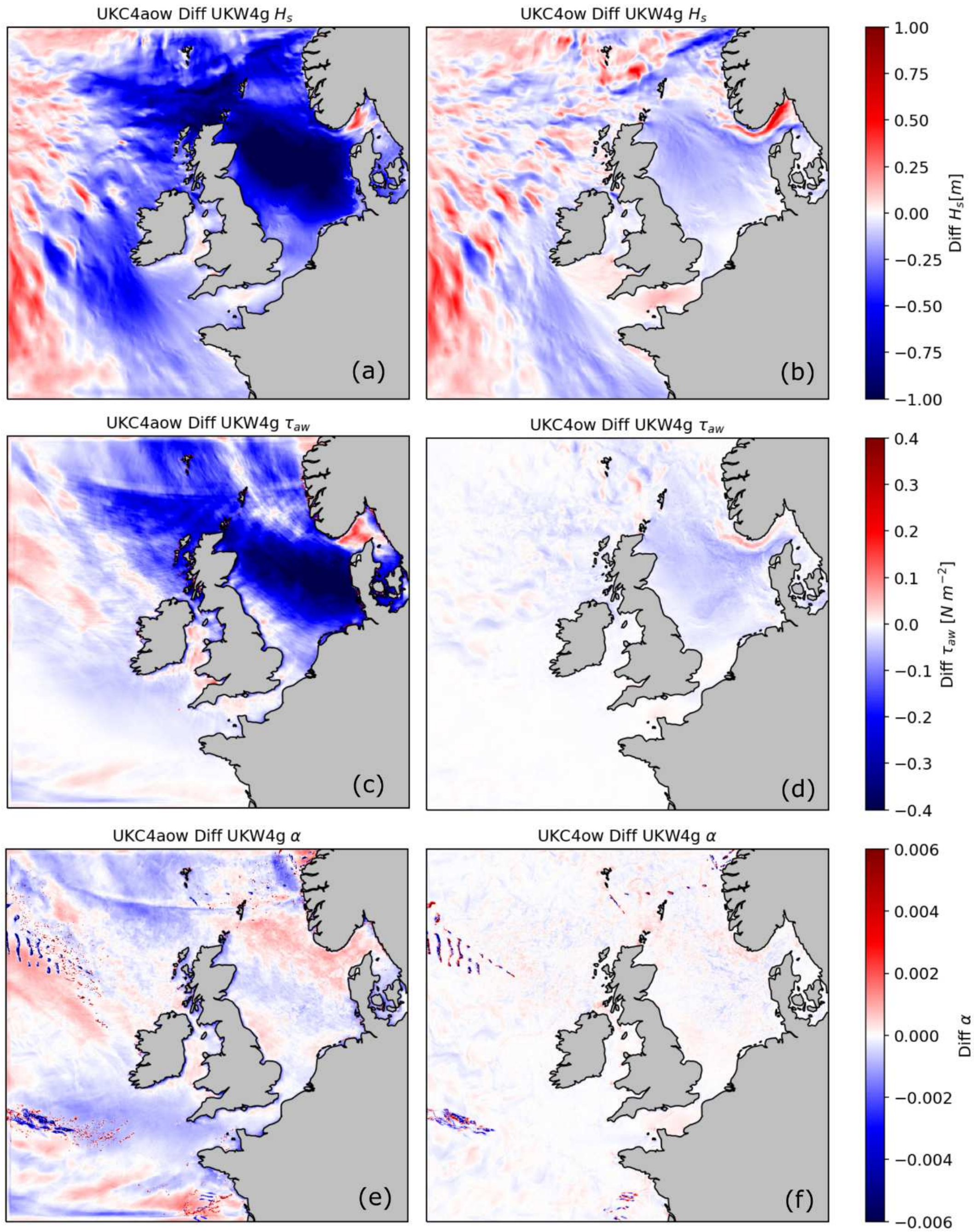

Figure 10 Mean difference in (a,b) significant wave height (H_s), (c,d) wave supported wind stress (τ_{aw}) and (e,f) Charnock coefficient (α) between UKC4aow and UKC4ow, and the control model run (UKW4g) across the entire domain during storm Xaver (refer to Fig 2a).

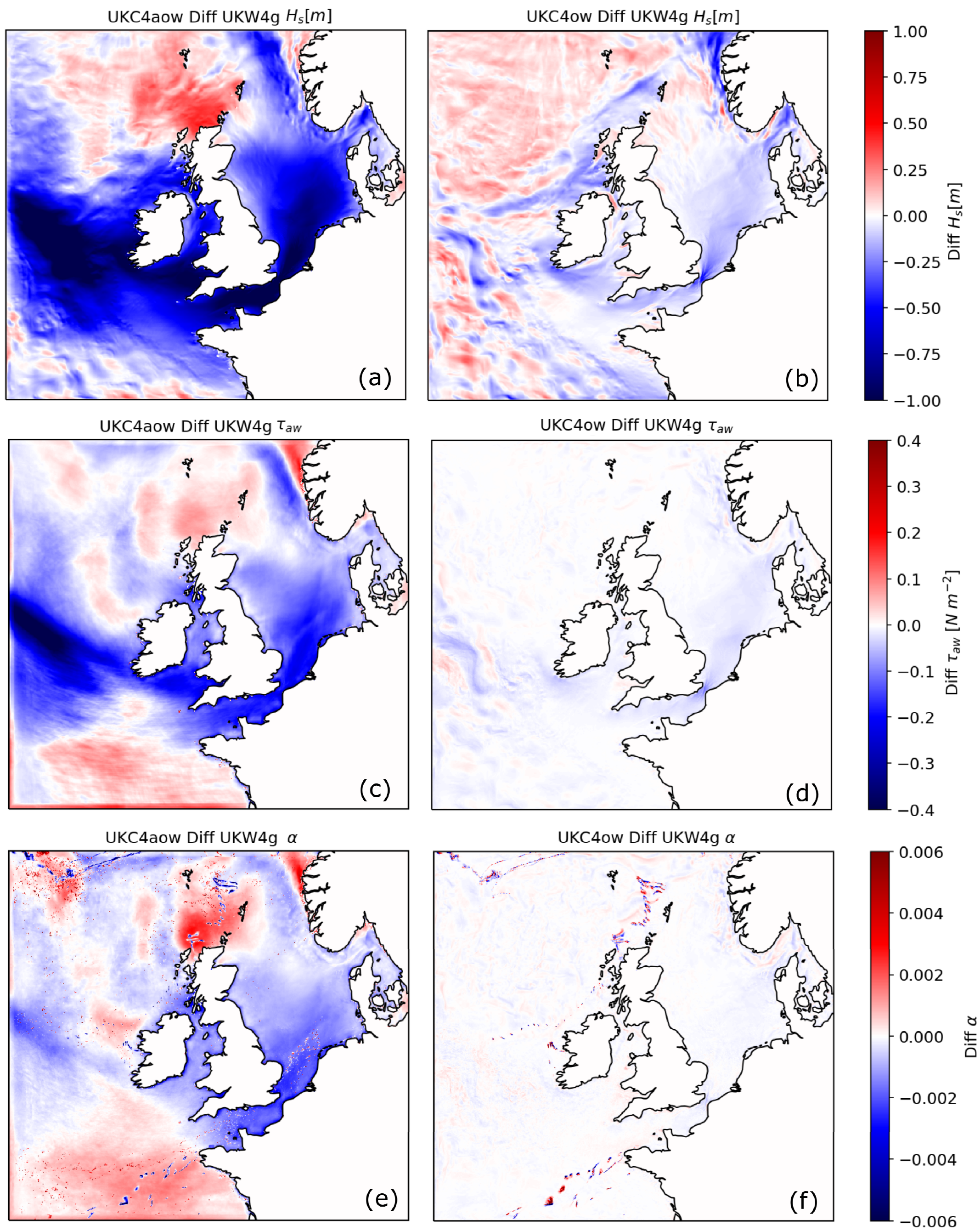

Figure 11 Mean difference in (a,b) significant wave height (H_s), (c,d) wave supported wind stress (τ_{aw}) and (e,f) Charnock coefficient (α) between UKC4aow and UKC4ow, and the control model run (UKW4g) across the entire domain during storm Ruth (refer to Fig 2j).

The fully coupled system consistently shows slower wind speeds during the storms (on-shelf and off-shelf bias of -0.566 m s^{-1} and 0.89 m s^{-1}, respectively; relative to -0.18 m s^{-1} and 1.31 m s^{-1} for the other experiments; Table 5) and this is reflected in a weaker wave growth with respect to the other experiments. UKC4aow underestimates wave growth during the storms for those areas in the lee of land. UKC4aow significant wave heights are smaller for waves >5 m. If we look at two on-shelf locations, one in the UK SW approach (Fig. 12 - left panels) and the other one in the Southern North Sea (Fig. 12 - right panels); we observe that despite a very similar wind signal in all experiments, the fully coupled model does not capture wave growth accordingly. One could argue some effect of the high-resolution winds; however, comparison of the wave–only simulation forced by high resolution winds (UKW4h) versus coarser (UKW4g) resolution winds finds almost exactly the storm wave growth behaviour in both waves–standalone experiments for these particular locations. Contrary to expectations, there seems to be a remarkable agreement in W_s between hi-res and global NWP atmosphere at both in-situ platforms in Fig. 12. Typically, our hi-res results indicate hi-res models tend to have the highest wind bias against in-situ observations (not shown); however, this is not very evident as both sites are relatively sheltered/coastal locations. It is also worth noting that in-situ observations of wind speed must be interpreted with caution as we do not have always the certainty that observations are referenced to 10 m.

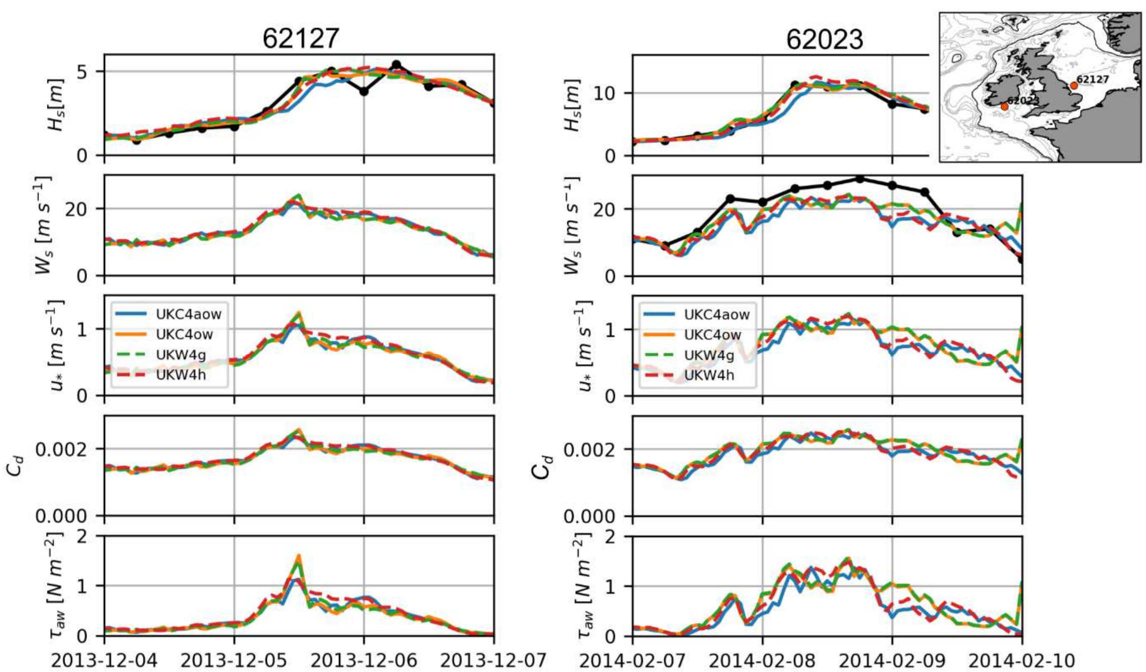

Figure 12 Timeseries of modelled significant wave height (H_s), wind speed (W_s), friction velocity (u_*), drag coefficient (C_d) and wind stress (τ_{aw}) during storm Xaver (left panels) and Ruth (right panels). 6-hourly observed in-situ H_s and W_s are also presented in top panels. The exact position for the specific locations (Cleeton - Southern North Sea, 62023; Irish Sea, 62127) are specified in the top right inlet.

Most of the momentum transfer to waves takes place through the generation of short high-frequency waves that are represented within a parametric tail of the wave action spectrum in wave models. Wave supported stress by shorter waves is a function of Charnock coefficient (sea state dependent, α) and wind friction velocity (u_*). Large α are more representative of higher W_s and younger seas; however, there is a negative feedback between the wave and the atmosphere as winds are reduced in excess and Charnock at high wind speeds is very variable in UKC4aow (c. 9% variability). Indeed, α in UKC4aow is larger (when comparing it with the other experiments) in some of the locations where the storm is underestimated (see Fig. 10), probably a sign that the wind sea is still developing (smaller wave age, not shown).

Fig. 13 shows the difference of ratio of momentum between the atmosphere and the surface waves (τ_a/τ_{aw}) computed using fully coupled UKC4aow and ocean–wave coupled UKC4ow relative to the waves standalone model UKW4g. The total atmospheric flux in WW3 is computed using the relationship

$$\tau_{a,ww3} = \tau_v + \tau_{aw}$$

where τ_v is the viscous stress and τ_{aw} is the momentum flux from the atmosphere to waves, also known as wave-induced stress. The ratio of momentum as per WWIII, $\tau_{a,ww3}/\tau_{aw}$, is then compared against the ratio of momentum using $\tau_{a,UM}$ for the atmospheric component (i.e., $\tau_{a,UM}/\tau_{aw}$). We know that the larger this ratio of momentum is, the less efficient the wave growth. During the storms, slower wave growth consistently matches with larger ratio of momentum budget (i.e.,$\tau_{a,WW3}/\tau_{aw}$) in UKC4aow (Fig. 13a) relative to the other models (Fig. 13b). When comparing $\tau_{a,WW3}/\tau_{aw}$ (Fig. 13c) and $\tau_{a,UM}/\tau_{aw}$ (Fig. 13d), it is observed that main areas affected by the storm present greater $\tau_{a,WW3}/\tau_{aw}$. Hence, for the case of UKC4aow, wave model τ_a from neutral winds is lower than direct τ_a from the UM. This leads to weaker wave growth, therefore comparatively younger seas and larger Charnock reducing UM wind speeds and weakening both UM and WWIII τ_a.

This suggests that a modification of the coupling in UKC4aow, to pass a stress directly from the UM with no feedback from the wave model (i.e., using $\tau_{a,UM}$ and not passing Charnock coefficient) should reduce the differences with the other systems on the shelf. Hence, coupling the wind speeds to the wave model and allowing the wave model to calculate the momentum transfer from the atmosphere to the waves and the ocean underestimates the transfer by a few percent, as previously discussed by Edwards (2020). The implication is that model skill for the fully coupled model is poorer than in ocean–wave coupled and waves–standalone models. In agreement with latest studies using other MO regional models (e.g., Indian regional model; Edward, 2020), next steps to improve the forecast of rapid developing waves using the fully NWS regional coupled model should involve alternative designs in the wave model set-up (e.g., source terms parameterization) and/or coupling of surface stress in order to reduce friction at the surface and subsequent wind slowdown.

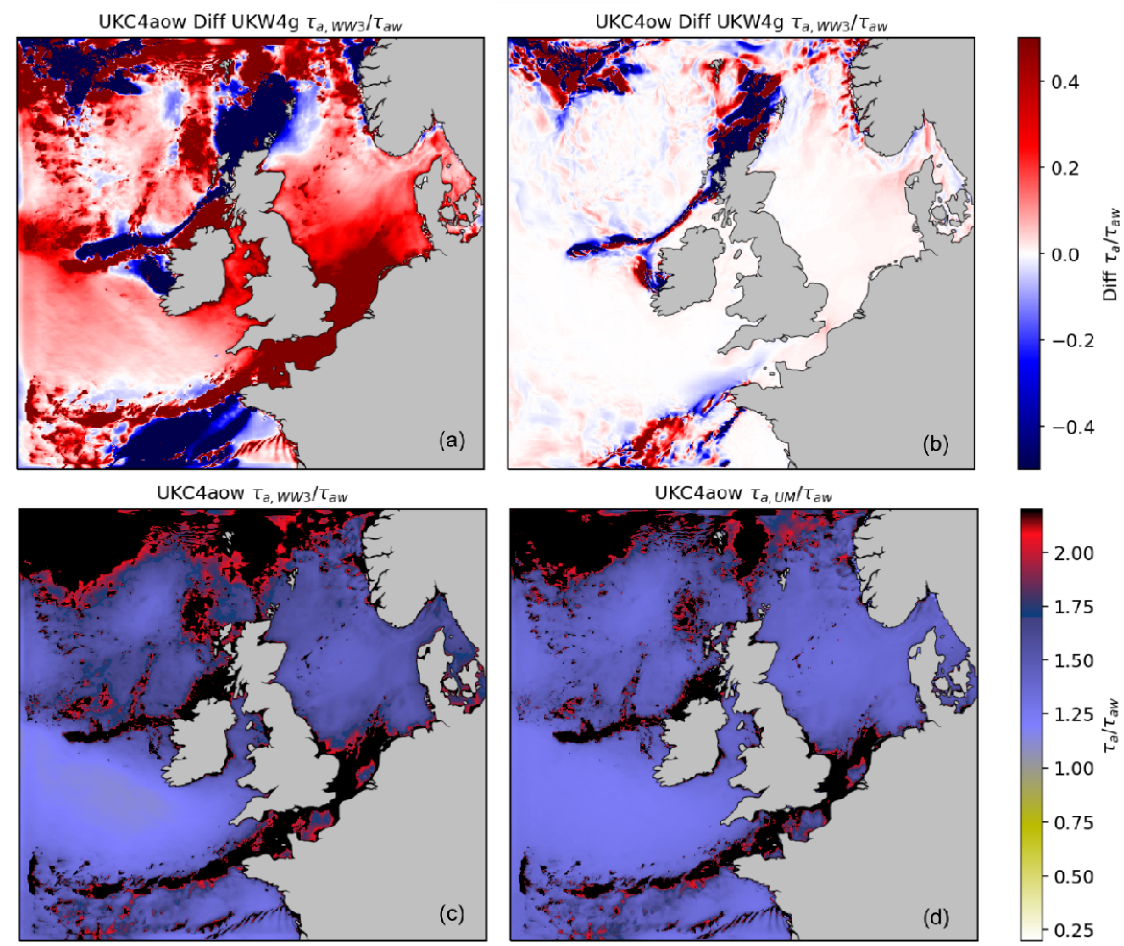

Figure 13 (a,b) Mean difference in average stress ratio τ_a/τ_{aw} between UKC4aow and UKC4ow, and the control model run (UKW4g) across the entire domain during storm Ruth (refer to Fig 2j). (c,d) Average ratio of momentum with atmospheric stress computed using WWIII balance $\tau_{a,WW3}/\tau_{aw}$ and UM $\tau_{a,UM}/\tau_{aw}$ for UKC4aow system during storm Ruth.

7. Conclusions

This study analyses the coupling effects on the wave field during an exceptional period of extreme events (winter 2013/2014) using the MO Northwest shelf regional system UKC4 in its different coupled versions: atmosphere–ocean–wave and ocean–wave. The main conclusions from this analysis are:

- From the different levels of coupling, ocean–wave coupled has the best skill in reproducing wave fields during the storms on the continental shelf. Wave–only forced by MO global winds skill is similar but slightly worse in areas with important tidal modulation. The fully coupled model shows an increase in significant wave height (underprediction) bias of 1-3% and ~5% MSE relative to the other systems. This decrease in skill change is even greater when we compare wind speed where RMSD increases between 20 to 5% in most locations.
- The waves standalone current operational configuration (wind and current as forcing), shows the best overall skill scores. This is simply associated to suite discrepancies which result in improved agreement of the wind forcing for this experiment relative to the other ones.
- Literature normally points out that high resolution improves model performance. However, the atmosphere–ocean–wave coupled (with high resolution winds) shows an overall poorer skill score when comparing with the other systems. During the storms, the atmosphere–ocean–wave coupled system shows a positive bias in the sheltered coastal locations - where the wave generally is underpredicted by the rest of the models. Conversely, we find the opposite behaviour in the other locations across the NWS where the fully coupled model consistently under-predicts when waves are large or grow very quickly, not getting the wave growth right and missing the peak of the storms.
- Largest differences between the different levels of coupling are observed on the continental shelf during the storm episodes. These differences between the atmosphere–ocean–wave and the waves standalone can reach 10% and >15% of the total field for significant wave height and wind speed, respectively. Diagnostic variables such as total stress from the atmosphere to waves vary between systems even more (40% of the total signal) in those on-shelf areas affected by the individual storms. Differences between the ocean–wave coupled system and the waves standalone oscillate c. <2–5% of the total field.
- There is a negative feedback on the overlying atmosphere because enhanced friction reduces excessively the wind speed close to the surface, reducing model skill simulating surface wind waves by the atmosphere–ocean–wave coupled model. Additional testing is recommended using alternative designs of the wave model set-up (e.g., source terms parameterization) and/or a possible modification of the

coupling of surface stress in order to improve the forecast of fast growth waves in the UK continental shelf.

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