Author response to RC1: "Evaluating the impact of atmospheric forcing resolution and air-sea coupling on near-coastal regional ocean prediction" by Huw W. Lewis et al.

We thank RC1 for their constructive comments, which have led to improvements in the revised manuscript. Their contribution has also been acknowledged in the revised manuscript. A detailed response to the 'Major comments' and 'Minor comments' are provided further below.

RC1 also highlighted a particular concern, which we address directly, that:

"*….I got a slight impression, that the detailed evaluation of the improved system (UKC3) is separated into a second article to increase the number of publications (just using only the time period in summer and additional a slightly smaller area of interest….. There is also an article about the evaluation of the wave coupling (doi: /10.5194/os-2018-148; did not read this one), which is introduced in the GMD discussion paper….*"

The introduction text has been amended to be clearer about the distinction between the UKC3 description paper in GMD and this manuscript, but we also clarify the situation here.

The UKC3 system description paper has now been accepted for publication in GMD, and aimed to provide a high-level overview of system performance across 4 different times of year and evaluating results across atmosphere, ocean and wave components for the whole North West Shelf domain. The focus of that work is on the impact of coupling, and in particular on the effect of introducing new wave feedbacks within the ocean component in UKC3 (relative to UKC2 capability).

In contrast, this paper aims to take a much closer evaluation of the different atmospheric forcing on ocean results only, and to better define the impact of coupling we have conducted a series of new simulations not discussed at all in the GMD paper – referred to as FOR_HI, pCPL_WIN and pCPL_RAD here. The assessment of the FOR_HI results relative to FOR_GL is important to identify the impact of changing atmosphere forcing from global-scale to regional-scale, and therefore enables some measure of the additional impact of representing the feedbacks by then comparing coupled results with FOR_GL.

This paper focuses on only a small region to better highlight the changes in near-coastal regions, where we could make use of radiation measurements over sea at L4. A summer simulation period is selected as representing the period when atmosphere forcing and coupling changes had most impact. This also coincided with a period of good observational data coverage at L4, where we had access to both atmosphere and ocean observations. Of course, a more expansive discussion looking at a number of different times of year and locations within the domain would be desirable, but not feasible while also providing the kind of detailed evaluation advocated by RC1 as "*This evaluation is important and should be publish*".

In summary, the current manuscript is fundamentally different to the UKC3 system documentation paper, and no material initially intended for that paper has been "*separated*" into this paper as suggested. We therefore appreciate the editor continuing to consider the submitted paper for the CMEMS Special Issue, revised in light of reviewer comments.

The Ocean Science submission on the impact of wave coupling referenced by RC1, is also briefly cited in this paper, but concerns evaluation of wave impacts in the AMM15 system over a 2-year trial period (2017-2018) based on the operational ocean forecast configuration with/without data assimilation, and using global-scale ECMWF forcing throughout. Beyond the common domain and use of the NEMO wave coupling configuration, there is very little practical overlap between the themes of the ocean-wave coupling paper and this manuscript.

Author response to RC1 Major comments:

1. *I suggest to focus only on changes in model resolution and air-sea coupling here and mainly use the experiment CPL_AO and not CPL_AOW for comparison with uncoupled simulations (FOR_GL and FOR_HI) as CPL_AOW also includes the wave coupling. Although the CPL_AOW shows the best results, it would not be clear if differences arise from the air-sea coupling or the wave model coupling, especially as differences of wave model coupling are only shortly described in the section about near-surface wind speed. In addition, there is the other article submitted to Ocean Science about the wave coupling, which probably discuss this topic in detail.*

We made a deliberate choice to show both CPL_AO and CPL_AOW results where possible, and consider the use of wave coupling to be important in general. The summary results (e.g. Fig. 2) show the differences between CPL_AO and CPL_AOW to be small at this time of year relative to the influence of including air-sea coupling, or the change in atmospheric forcing. Demonstrating this consistency is considered to be a useful result. The impact of wave coupling is discussed in more depth with regard to wind forcing, as the feedback between the wave model and atmosphere through the Charnock parameter has the potential to improve the wind forcing – here we argue that the SST-wind feedbacks are in fact more important, and that the coupling cannot 'correct' for the change in wind characteristics in the regional scale system relative to global.

As noted above, the 'other article submitted to Ocean Science about wave coupling' discusses a completely different experimental design over a two-year trial period with a focus on ocean results in the context of the operational CMEMS NWS system. Critically, there is no use of a regional scale atmosphere, or any ocean-atmosphere or wave-atmosphere feedbacks represented in the 'other article'.

2. *The current article is structured in a way that it describes the different physical properties separately including all model experiments, which makes it difficult to get the connection of all changed processes. Therefore, I would like to suggest to change the structure of the results section of the article as follows and extent the physical analysis.*
    a. *The evaluation of the newly coupled system and the improvement compared to observations should be located in the GMD paper (is there also the Performance improvement between the UKC3 and UKC2 system shown?). Therefore, only a short overview should be given here (may also include the CPL_AOW simulation).*

b. *Then show how the uncoupled system changes with increasing resolution (FOR_GL vs. FOR_HI). Mention how the differences in the general physics influence the results (especially the atmospheric convection). Please describe here possible changes in the physical processes due to the increased resolution and how they influence the others (e.g. how C2 changes in radiation influence, SST, ocean currents, etc). What causes the changes? ...*
c. *Then compare the high resolution FOR_HI with the coupled system CPL_AO. How is the feedback of ocean to atmosphere changing wind speed and direction, and radiative fluxes. How are clouds influenced by changes in winds and how do they change the radiative fluxes. How is the ocean state changed e.g. how are ocean currents changed? Explain the origin of the larger scale patterns occurring in the differences in SST, wind and SW. When looking at these differences by eye, there might be similarities. If yes, what are their origins? Mechanism that shifts clouds leading to changes in radiation in the study area, explaining the differences in the mean fields and e.g. the biases in the SST? ...*

The current manuscript Results section is structured to

i) Sect. 3.1: provide a brief overview of the SST results, setting the context of the experiments including FOR_HI and OSTIA results, which are not discussed at all in the GMD paper referenced.
ii) Sect 3.2: discuss the evaluation of SST across the Celtic Sea sub-region and relative to the L4 observation point in particular, referenced later in the paper.
iii) Sect 3.3: consider the different heat budget in all experiments.
iv) Sect 3.4: consider the wind forcing in all experiments.
Sect 3.5: explore partially coupled sensitivity experiments

We considered the suggestion of RC1 to effectively re-order the discussions of Sect 3.3 and 3.4 in particular to focus on both heat budget and wind forcing changes for a) FOR_HI vs FOR_GL, then b) CPL_AOW vs FOR_HI. On reflection we have kept the same overall structure however, noting it is helpful to compare all experiments relative to a particular observation or diagnostic (e.g. Fig. 7, 8, 10) within the same broad discussion. To first order, we also find that the heat budget and wind forcing of all regional scale simulations can be distinguished as a group from the FOR_GL forcing (e.g. Fig. 7, Fig. 10.). We have though revised these sections in light of the comment above, separating out more clearly the discussion of FOR_HI vs FOR_GL from CPL_AOW vs FOR_HI. In particular, note the revision of new Fig. 5 and new Fig. 6 to make this separation more explicit.

The discussion encouraged by RC1 in bullet c. above on the relationship between SST, wind and SW is better represented in the revised manuscript, including the encouragement of RC2 to consider the change in SST comparing OSTIA (used as a fixed daily boundary condition in FOR_GL and FOR_HI atmosphere model simulations) with CPL_AOW (e.g. Fig. 3f)) and its links to the changes in heat budget (e.g. Fig. 6d)) and wind (Fig. 9f) results.

3. *Please also investigate the changes in physical processes in detail during the other seasons. Are there differences to the summer season?*

As discussed above, we consider the extension of the current paper to results during other seasons to be out of scope, given the emphasis on a period when atmospheric forcing and coupling was considered to have largest effect. We better highlight this choice in the Introduction and Conclusion of the revised manuscript. Were we to add the suggested detailed analysis during other seasons, the manuscript would risk becoming overly long, and lose some of the detail requested by RC1 and RC2 in reviewing the current work.

4. *Please make sure that in the conclusion and discussion, it is clear what the new finding of this study is compared to earlier studies and the GMD discussion paper.*

The contrast to the GMD paper is explained more clearly in the revised Introduction. The first 3 paragraphs of the Conclusion refer to a summary of new findings of this study, and a characterisation of the sensitivity of ocean SST simulation over the NWS to choice of atmospheric forcing. The comparison to the GMD discussion paper is provided in the 4th paragraph.

5. *There are some results "not shown", which should be. For example: - Page 8, Line 10: please show the examination of the cloud field - Page 9, line 16: please show the std - Page 9, line 25: please show the time-series of Qns*

The cloud fields are not shown in interest of brevity, and as the fields are not readily available within the archived global-scale ocean model forcing fields (FOR_GL).

Other requested plots have now been added to the revised manuscript, within the updated Fig. 8 (std in d)-f)) and updated Fig. 7 (time series of Qns).

6. *I would like to suggest to leave out section 3.4 (Partially coupled sensitivity experiments) as coupling only wind or radiation would lead to inconsistencies in the fluxes between atmosphere and ocean, which in my point of view would make interpretation difficult if not impossible.*

RC1 is correct to highlight the inconsistencies in fluxes between atmosphere and ocean in the partially coupled sensitivity experiments. We highlight this point more clearly in the revised manuscript in light of this comment. However, given the encouragement of RC2 to expand rather than remove this section, we consider there still to be value in the results – indeed they help to illustrate the relative impact of the heat budget and wind forcing in isolation within the system, and enable us to conclude that coupling both wind and radiation leads to improved results although the evaluation of the regional-scale wind field is worse than the global scale atmosphere forcing.

7. *During comparisons sometimes only snapshots of one particular time point is shown. Are these snapshots representative for the 10 day period?*

Revised spatial plots in Fig. 3 (SST differences relative to OSTIA), Fig. 5 (heat budget terms and differences between FOR_HI and FOR_GL), Fig. 6 (differences in heat budget between CPL_AOW and FOR_HI) and Fig. 9d)-f) are all now consistently presented as 10-day means. This does mask some of the variability in fields such as the heat budget terms, but does provide a more representative illustration of results – indeed demonstrate that the snapshots presented in the original manuscript were generally representative.

Author response to RC1 Minor comments:

- *There are references used that are still in preparation, submitted or in review (Tonani, et al. 2018, Bush et al., 2018, Lewis et al., 2018c). I'm not sure if this is allowed in Ocean Science. If they are published as discussion papers it might be possible, but what about the ones in preparation?*

The references list has been amended with relevant doi to reflect the updated status of papers currently in review in Ocean Sciences. The only reference still listed as in preparation is Bush et al., (2018), which we anticipate to be submitted and have a citable doi very shortly and in time to be referenced were the current manuscript accepted for publication.

- *Page 2, line 17-20: Please make two sentences out of it as it it hard to read.*

This sentence has been shortened in the revised manuscript.

- *Page 2, line 21-23: how are the mesoscale ocean processes changed?*

An additional sentence has been added to more fully explain the results of Lebaupin Brossier et al. (2011).

- *Page 2, line 28-29: Put here also other references (e.g. the examples used in the following)*

In accordance with a related comment from RC2, the example citation has been updated and highlighted as offering a review of regional coupled studies in the revised manuscript.

- *Page 3, line 30: In this study: do you mean in the experiments FOR_GL and FOR_HI? Please clarify. Do atmosphere and ocean have the same model domain?*

Yes, and this is now clarified in the revised manuscript. The FOR_HI atmosphere and ocean model have the same model domain (as applied in coupled mode in CPL_AO and CPL_AOW simulations). This is also explicitly clarified in Section 2.1.

- *Page 4, line 19: please include a line break after "provided by Bush et al. (2018)."*

This is done in the revised manuscript.

- *Page 5, line 8-9: please provide a short description or a reference to the "double penalty" effects*

This has been added and a reference provided in the revised manuscript.

- *Page 6, line 28-29, "potentially link" Please investigate if it is linked or not?*

RC2 highlighted the difficulty in attributing the scale of SST variability to either the diurnal heating cycle or to tidal variations. In practice, the SST variability at any location will be some combination of these factors. We argue that the SST variability at L4 is mostly driven by the tides, but of course there is some influence of diurnal heating. It is not really possible to be any more definitive than 'potentially linked' in a paper of this scope, nor considered so important for the main conclusions drawn.

- *Page 7, line 8-11: Please also compare with model results in the morning to clarify if it is an artefact. Maybe also check it by using less neighbourhood grid cells for averaging.*

The vertical profile results presented in this study were available as daily mean diagnostics, so it is not easily practical to look at sub-daily patterns. The main aspect of interest from Fig. 4(b) is in contrasting the daily mean profiles from the four model experiments, using the CTD observations from L4 as a reference.

- *Page 7, line 12: Can you give a physical explanation for the improvement?*

We attribute the improvement to representing air-sea interactions within the coupled system, and the impact not only being apparent at the surface. Additional text has been added in the revised manuscript.

- *Page 8, line 20: cloud on 24 July → cloud cover on 24 July*

This has been amended, also in line with the related comment of RC2.

- *Page 8, line 24: This could be related → Is this a hypothesis or is it related to*

This is indeed a hypothesis. The text has been amended to be clearer.

- *Page 9, line 14: with "patches" you mean the small scale spatial variations in the fields, right? If yes, do they origin from physical processes, (e.g. from sea surface roughness) or is it just the increased noise that occur in higher resolution models*

Yes, we intended to say small scale spatial variations in the fields, although the 'patches' here refer to the variations where there is relatively reduced radiation. The text has been amended in the revised manuscript to clarify. We do not characterise source of the variations as "just the increased noise" but reflecting some combination of the explicit rather than parameterised convection, scale-dependent physics and different grid sizes in the higher resolution models. As discussed in response to RC2, attributing changes to resolution vs physics is a challenge.

- *Page 9, line 20-24: Please reduce the length of this sentence by separating it into at least two and eliminate "might be expected"*

The original sentence has been removed in light of the response to the comment above, and in line with the comments of RC2 in this regard.

- *Page 9, line 32-33: For clarification, please reformulate the sentence*

The sentence has been reviewed and reformulated as suggested.

- *Page 12, line 4: further still by including → further by including*

The sentence has been updated.

- *Please note if the forecasting system includes data assimilation. In case it does, mention the data that is assimilated in the method section.*

All regional-scale ocean and atmosphere simulations discussed in this paper are free-running without any data assimilation. This has been explicitly mentioned in the updated Section 2.

- *Please mention in the method section, which parameters are used as atmospheric forcing for the uncoupled simulations and which parameters are exchanged between atmosphere and ocean and where the fluxes are computed.*

This has been added in the updated Section 2, in line also with the comment of RC2.

- *In table 2 and table 3 and page 10, line 25: FIX_GL und FIX_HI written instead of FOR_GL and FOR_HI, please correct.*

Corrected.

- *Please carefully check the reference list. For example, Valcke et al. (2015) is mentioned in the text but is missing in the reference list.*

The reference list has been amended in the updated manuscript, and the missing Valcke et al. reference changed for a more recent reference to OASIS in light of RC2 comment.

- *Figure 1a) please increase the lines in the colorbar to be able to identify the different colors*

Corrected.

- *Figure 1b) what are the black and yellow dots? The Celtic Sea study are is partly located outside the UKV atmospheric grid. Does it impact the model results?*

The dots are indicative of the volume of data from each location during the period of interest, as now clarified in the updated figure caption. The yellow dot indicates the location of the L4 buoy. The caption has also been updated to clarify the 'outside the UKV atmospheric grid' – to highlight only that the inner region of the variable grid atmosphere domain has a regular spaced grid resolution, with stretching outside. We do not consider that this impacts the model results.

- *Figure 3) please use the same blue-red colorbar in a) and b) as used in c)*

In the original manuscript, Fig. 3c) presented model differences while a) and b) were model fields, so it was consistent to have different colorbars. In any case, Fig. 3 has been updated in the revised manuscript and its presentation and consistency of colorbars improved.

- *Figure 4a) and 4b) please increase the limits of the y-axis to include the max. difference in figure a). Also label the x-axis with the days (at the moment always 00.00)*

It was decided to merge some of the content between the original Fig. 3 and Fig. 4 in the revised manuscript given the suggested change in focus to consider spatial model fields relative to OSTIA also.

- *In Labels of Figures 3, and 5-11 need to be larger to be readable in a printed copy*

All Figures in the revised manuscript have been updated in light of this comment and in response to other reviewer comments.

Author response to RC2: "Evaluating the impact of atmospheric forcing resolution and air-sea coupling on near-coastal regional ocean prediction" by Huw W. Lewis et al.

We thank RC2 for their particularly constructive and detailed review comments and have amended the manuscript in response. Their contribution has also been acknowledged in the revised manuscript. In addition to correcting the list of 'Other comments' provided (see below), and a review of the full document in light of RC1 and RC2 comments in general, the following substantive changes have been addressed:

- Better justification for only considering one month in summer in this study,
- Improved linkage of relevance of this finer-scale ocean work with suggested references from the regional climate modelling community,
- More explicit reference to the positive but secondary added value of wave coupling,
- An updated presentation and discussion comparing SST simulations with OSTIA,
- Discussion of the initial condition bias, and opportunities for use of ocean analyses in future research,
- Better attribution of some heat budget differences to the different SST state in forcing and coupled atmosphere simulations,
- Expansion of the discussion on partially coupled results,
- More careful reference to resolution and physics changes between the global NWP and km-scale regional atmosphere forcing.

Author Response to RC2 *General comments*:

1. *The justification for only considering one month in summer is however missing.*

We agree, and have briefly provided a better explanation of the motivation in the last paragraph of the Introduction on p3. This change is also in line with a similar request from RC1 to more clearly articulate these choices. In brief, we selected to assess the July 2014 results and focus on a relatively small part of the model domain in order to provide a more detailed discussion of the impact of atmospheric forcing and coupling on near-coastal SST results, for a period identified by the overview discussion of Lewis et al. (2018b) as being most sensitive to coupling.

2. *Such kind of evaluation is quite often done in the regional climate modelling community (e.g. Béranger et al., 2010; Akhtar et al. 2018a,b) and it could be relevant here to put forward the novelty of considering ocean forecasts with a very fine coupled system and the inherent difficulties.*

The role of atmospheric forcing and coupling is indeed more routinely discussed in the context of typically coarser-scale regional climate modelling activities and it would be useful to contrast this with the present study. This has been addressed in an updated Introduction in the revised manuscript.

3. *The added value of the wave coupling is also not so well highlighted.*

We summarise in Sect. 3.1 that “there is some additional value evident from coupling information of the wave state to ocean and atmosphere components in CPL_AOW (MD = 0.20 K), although this is of secondary importance to the impact of either changing atmosphere resolution or ocean-atmosphere coupling”, and in Section 3.3 that “the influence of wave coupling feedbacks is generally small at this time of year”. The aim of presenting both CPL_AO and CPL_AOW results is both to demonstrate the performance of a fully coupled regional system, i.e. with wave coupling as an important component of the earth system at these scales, but also provide a more traceable comparison of the impact of coupling relative to the ocean-only results. This also addresses one of the comments of RC1. In light of the comment above, a new summary sentence has been added to the Conclusions to again highlight the relatively minor impact of wave coupling for this region and time of year.

4. *The key point in the ocean flux forcing which is the SST inconsistency between the one simulated in the ocean model and the one used at the surface boundary of the atmospheric model. It obviously controls the differences in several heat budget terms and very likely the differences in wind between CPL_xx and FOR(_HI) but it is never mentioned here.*

This is a fair challenge and an omission of the reviewed manuscript. The new comparison of SST against OSTIA (which provided the SST surface boundary of the atmospheric model) in the revised Figure 3 helps to highlight this point, and RC2 is correct to highlight the close spatial distributions of changes in SST and the change in sensible heat and latent heating in particular. This is now addressed in the revised manuscript in discussing the heat budget results of modified Fig. 6.

5. *The robustness of the SST improvement (with the higher resolution forcing and coupling) that appears a little altered by the fact that it seems to be more a spinup effect, with a reduction of the initial bias during the first days of simulation.*

We agree that longer-term simulations of the fully coupled simulation would be required to evaluate how robust the improvement is. However, we argue from Fig. 2 that the improvement becomes well established and is relatively constant by the second half of the month at least. This motivates us to discuss the 10 day period considered in most detail as being representative of a relatively steady state. Another interpretation of the comment on spinup, is that the simulations diverge relatively quickly in the first days of simulation, driven only by a change of atmospheric forcing or introduction of the atmosphere-ocean feedbacks.

6.

7. *The use of partially coupled sensitivity experiments seems very promising, but their results are too briefly discussed.*

We appreciate this encouraging comment, and have provided some expansion of both the motivation for running the partially coupled sensitivity results and their assessment in the revised manuscript (Section 3.4). We balance this with addressing the concern of RC1 that they had less value given that the heat and wind terms are by definition not in equilibrium in these simulations. They aim to help better attribute the previous results described.

8. *I'm finally interrogative about the large impact of the higher resolution which is always highlighted by the authors instead of the impact of the physics (qualified as a smaller impact). But for me this is connected, especially over sea, far offshore. I suggest to clarify or discuss more this point.*

This is a valid concern, and a topic of discussion for the authors in the original assessment of the results in this study. The conflation of both resolution and physics changes between global NWP and what is characterised as the 'high resolution' forcing makes this a particular challenge. We have been encouraged by this comment to be more precise where possible in the revised manuscript as describing the global-scale and regional-scale forcing as being indicative of two readily available sources of atmosphere information, with the regional-scale also able to be applied with feedbacks. Changes have been made where relevant in the revised text. The paper title has also been updated in view of this comment.

The main reason for quoting the spatial grid resolution as dominating over physics changes originates from considering the larger spatial variability of forcing terms in FOR_HI than FOR_GL for example. We aim to be more careful in the revised manuscript that it is not clear we can attribute this directly to a resolution change alone.

Author response to RC2 Specific comments:

9. *Page 6, lines 2-3: "This indicates improved SST prediction can be achieved for the NWS when applying the high resolution." In my opinion, this conclusion is too rapidly set. Figure 2 shows mostly the stronger cooling during the first days of simulation (till 5 July) in FOR_HI, CPL_AO and CPL_AOW, correcting more efficiently the initial warm bias. Considering the overestimation of the wind in the higher resolution forcing (coupling), this is a possible ocean response to the initial shock with a larger effect of the vertical mixing. How do the mixed layer's depth and thermal content evolve?*

While the statement as written is correct (i.e. the SST Mean Difference for FOR_HI is lower than found for FOR_GL results), the tone of this line has been modified in the revised manuscript to be less definitive at that point, as we accept that it can be read as too definitive a conclusion.

The vertical profile in revised Fig. 4(b) shows the FOR_HI, CPL_AO and CPL_AOW simulations to have deeper mixed layers, consistent with RC2's comment, and with the persisting warm bias in FOR_GL. However, later discussion of the pCPL_RAD results show that by only applying the higher resolution (overestimated) winds does not diminish the warm bias in the same way, rather it increases over the first days of simulation and settles at order 2 K warmer than observations (Fig. 12). This further supports the value of the partially coupled simulations in drawing conclusions from the study (see response to comment 6 above).

10.

11. *If possible I suggest to test new initial conditions, more realistic, such as such as ocean analysis that are available in the CMEMS catalogue or at least a larger discussion about the relative importance of the forcing compared to the model initialisation.*

We expand on this valid point in the revised Conclusions. While it is not practical to test new initial conditions in the present study (e.g. covering the period of interest), the relatively recent implementation of the 1.5 km resolution AMM15 ocean model configuration to provide CMEMS NWS MFC products (e.g. Tonani et al., 2018) does now offer a source of ocean analysis from the same system as used here, which should be valuable to support future research work.

12. *Between 18 and 24 July, it seems there is a warming in FOR_GL whereas SST is stable in FOR_HI and CPL_xx. How is it explained?*

The period highlighted by RC2 is apparent both for the domain-wide results in Fig. 2 and to some extent reflected in the location-specific comparison with observations at L4 in Fig. 4. While we do not provide detailed consideration of the evolution of FOR_GL results, the difference between FOR_GL and FOR_HI net shortwave radiation over period 20-30 July 2014 in the revised Fig. 5(e) highlights the relatively higher solar heating in FOR_GL described in the paper. Considering only the Celtic Sea region, the difference in Fig. 5(e) is focussed towards the south-west approaches, which coincides with the region of largest warm bias over the same period illustrated in the revised Fig. 3(d).

13. *Page 8, lines 8 to 15: "(. . .) The impact of coupling on (. . .) QLW is dominated by random changes in the spatial distribution of convection. (. . .) There is also some evidence that the latent heat flux is increased in those near-coastal regions identified as being cooler in CPL_AOW than FOR_HI, where the coupled simulation SST was in closer agreement with observations in Fig. 3(c)." To well consider the differences in the heat budget terms between the coupled runs and FOR_HI, the comparison of the CPL_xx and OSTIA SST field(s) must be shown. I think it explains at first order most of the differences found in the long wave upward radiation, latent and sensible heat fluxes. The differences in the convective cloud location play also, but at a second order. The last sentence is particularly confusing for me as it mixes information about LH, differences in SST simulated by CPL and FOR_HI and the validity of the CPL SST against observations. But what about the comparison between OSTIA and the in-situ observation in this region? Please revise.*

Comparisons between the FOR_GL, FOR_HI and CPL runs relative to OSTIA are now presented in a substantially revised Fig. 3. Time series comparisons relative to OSTIA are also now provided in Fig. 2 and Fig. 4 following this encouragement. The results discussion in Sect. 3 has been amended where relevant to describe these comparisons. We consider this provides a more coherent discussion than the original manuscript in line with the comment from RC2 above.

14. *Figure 6 (i-l): Please, adjust the scales to better show the differences. To be fair, it might be shown as relative differences (in %) instead. Very likely, the differences in the wind field are also controlled by the differences in SST. See Chelton and Xie (2010) or for example Lebeaupin Brossier et al. 2015 (Fig. 8a), Meroni et al. 2018 (Fig. 6).*

A version of Fig. 6 considering % differences was also prepared for the original manuscript, but changes were disproportionately dominated by regions where mean fluxes approached 0 Wm^{-2}. The impact of changing atmospheric forcing and coupling has now been separated (following RC1) across updated Fig. 5 and Fig. 6, where the comparison of heat budget terms are presented on a clearer scale. We concur on the difference in wind field being controlled by differences in SST. See also RC2 comment and response on p11, line 13-15 below.

15. *Page 9, lines 20-24: "This provides some evidence that the differences…is driven mostly by the change in grid resolution and the change from parameterised to explicitly represented convection,…."*
16.
17. *Page 10, lines 14-16: "The contrast between the spatial variability of wind speed between FOR_GL and FOR_HI further supports the assessment in Sect. 3.2…"*
18.
19. *I cannot really capture where the contribution of the high-resolution can be separated from the physical behaviour/parametrisations of MetUM between the FOR_GL and FOR_HI forcings. I mean, far from the coasts, there is no reason for these differences apart the MetUM physics? In addition, connections between resolution and physics exist. Some physical parametrizations may depend on the grid resolution (and time step). Please, clarify how you distinguish the relative importance of physics compared to the benefit of a finer grid mesh.*

This reflect the RC2 Comment 7 discussed above, and is a valid query. Some of the key atmosphere physics differences are outlined in Sect. 2.1 As described in the response to Comment 7, the manuscript has been modified to take more care in describing the change of atmospheric forcing in terms of 'global-scale' and 'regional-scale', noting the link between grid resolution and physics choices. In particular, as noted in the paper, the main difference is in the treatment of convection explicitly at 1.5 km whereas it is parameterised in the global atmosphere model.

Author response to RC2 Other comments:

• *p1, lines 14-15: "Observations. . . data". Please, revise the sentence as you do not only consider L4 observations. . .*

Revised – we aim to highlight use of both the 'routine' operational observations along with use of L4 as having co-located observations of atmosphere and ocean.

• *p1, lines 21-22: "...by global-scale NWP (0.7 K in the model domain) is shown..."*

Corrected in the revised manuscript.

• *p1, line 23: "...reduced (by 0.2K)."*

Corrected in the revised manuscript.

• *p2, lines 28-29: "A number of studies. . . (Lewis et al., 2018a)": revise citation.*

It is not clear what is intended by this request. The intention of this citation was to really indicate Lewis et al. (2018a) as a source of further references. We have modified the citation to reference the more obvious review paper by Pullen et al. instead, mentioned elsewhere in the Introduction. We hope this might be what was intended by RC2 here.

• *p3, line 7: "...for one of those periods in July 2014." The motivation(s) to dedicate this study to this reduced period must be given here.*

We agree, and have briefly provided a better explanation of the motivation in the last paragraph of the Introduction on p3. This change is also in line with a similar request from RC1 to more clearly articulate these choices.

• *p3, line 30: "...describing the surface heat and water budget..."*

Corrected

• *p3, line 31 "...NEMO using the 'flux formulation'...": Where (and how) is computed the wind stress?*

In the configuration used in this study, key_shelf is used in NEMO, and the wind stress is computed within NEMO based on 10 m wind components rather than applying the atmosphere model computed stress directly. This is clarified in the revised manuscript and a reference provided.

• *p4, line 8 (and lines 17-18): "the wave-dependent roughness Charnock parameter of 0.085 is used.": Could you precise if it is α or z0? If it is a constant, it is not wave dependent. . .?*

This is α. This sentence has been revised to clarify we mean a constant value used.

• *p4, line 17: "...assumed zero and a constant value..."*

Coorrected

• *p4, line 31: Valcke et al. (2015) is missing in the references list. Moreover, I think the citation for OASIS3-MCT is Craig et al., 2017.*

This correction has been applied in the revised manuscript.

• *p4, line 31: "...all information exchanged...". A brief list of the exchanged fields could be useful.*

This has been clarified with additional text at the end of Section 2.1

• p5, lines 7-9: I am happy to see here this comment concerning the 'double penalty' effect that is indeed of primary importance when comparing high-resolution modelling results with observations.

This is indeed an issue for evaluation of all such systems, and thank you for the supportive comment.

• p5, end of section 2.2: I am a little surprise there are only GTS data considered. Some other kinds of data could be available on the CMEMS website, in particular profilers to examine the vertical stratification or satellite data that allows a 2D coverage at the surface. Was it a choice to exclude them? And if yes, why?

We have focussed the analysis in this paper on the Celtic Sea region, and aim to make most use of the L4 buoy observations given the rare co-location of ocean and atmosphere observations, along with the radiation measurements. We also considered the co-located CTD observations from 28 July sufficient to provide some indication of the vertical profile in this region. The in-situ data on the CMEMS website (e.g. http://www.marineinsitu.eu/dashboard/) are in general consistent with those displayed in Fig. 1. We appreciate the encouragement to compare SST results with OSTIA, based on satellite data, which are now included in the revised manuscript (e.g. Fig. 2, Fig. 3).

• p5, lines 26-27: "Figure 2 demonstrates that all ocean simulations had the same initial conditions.." This is not something that must be demonstrated. That must be said before in section 2.

This sentence has been updated in the revised manuscript, although we consider it useful to remind readers of this from Fig. 2, particularly given that the later analysis focusses on the later period when the 4 experiments have diverged. The initialisation is indeed referenced in Section 2.1 to indicate all simulations have the same initial condition.

• p6, line27-28: "On several days (e.g. 20, 21, 23, 26 and 29 July) a tidally-forced heating signal of about 1 K is apparent." Well, it is not so apparent it is a tidally-induced heating or if it is a diurnal cycle.

This sentence has been revised to be 'tidally-dominated', while we agree there will be some influence of diurnal cycle at this time of year. The temperature range observed at L4 is large – greater than 1K on some days in fact, and there is observed evidence of 'double peaks' on some days through the series. We also consider the phasing of the time of maximum temperature to be progressively delayed from around noon on 20 July to late evening on 25 July for example.

• p6, lines 30-31: "The SST variability of FOR_GL is in general stronger than observed..." Where is it shown?

This sentence referred to the temporal variability of simulation results at L4 shown in the new Figure 4. In addition to being biased warm, the FOR_GL results show larger diurnal range than other simulations and than observed. This line has been revised in the updated manuscript to clarify that we mean temporal rather than spatial variability here.

• p7, line 19: "Surface heat budget..." Please change also everywhere after: 'Energy' can be potential or kinetic. . . 'Heat' is more precise.

This has been revised everywhere mentioned through the manuscript.

• p7, lines 29-30: "...and from CPL_AO and CPL_AOW coupled systems...": The flux fields for CPL_AO and CPL_AOW are not shown in Figure 6.

The comparison of coupled results with FOR_HI have been separated a little from the FOR_GL vs FOR_HI comparisons, following the suggestion of RC1, as reflected in splitting out new Figure 5 from new Figure 6. The manuscript has been revised to reflect the updated Figures, and the required correction identified here has been removed as part of this.

• p8, line 20: ". . . increased cloud cover on 24 July..."

This has been updated in the revised manuscript.

• p8, lines 26-27: "The warm surface temperature bias of FOR_GL at L4 appears to result despite rather than because of this difference however." Maybe mixing (i.e. cooling by entrainment) is also lower in FOR_GL?

Rather than offer a detailed discussion here, we are simply noting that the SST results cannot be well explained by looking at the local energy balance terms within a relatively small area around the L4 location, as shown in Fig. 7(b). Rather, the results become a little clearer when assessing the atmospheric forcing over the broader Celtic Sea region (Fig. 8). This sentence has been revised to clarify this.

• p9, line 8: "...consistently higher during night time...". Could you explain more this result?

The result described in line 7 and line 8 – i.e. higher net radiation from FOR_GL (contributing to higher SST) is resolved later on p9 from around line 20, where we relate the mean differences to lower spatial variability (lower standard deviations). This section has been revised further in the updated manuscript to attempt to clarify these discussions, noting earlier comments.

• p9, lines 18-19: "...both day and night..." ?? "...but typically of order 20-50% lower. . ." Where the '50%' comes from?

As requested by RC1, the time series of spatial standard deviation plots are now included in a revised Figure 8. This illustrates the substantially reduced standard deviation of radiation in FOR_GL relative to other configurations. The difference between daytime maxima through the period shown is considered to be of order 20-50% reduced.

• p9, line 27: Delete "the accumulated ".

Figure 8 has been revised, and now provides results as accumulated heat budget terms. This provides a clearer illustration of the differences between FOR_GL and FOR_HI forcing than mean values.

• p10, line 17: "The atmospheric forcing..."

This has been corrected. The original intention of "ocean forcing" was "The forcing of the ocean….", but this suggestion is clearer.

• p10, line 25: ". . . than FIX_HI..." FOR_HI?

Corrected in the revised manuscript.

• *p11, lines 13-15: "Some evidence of the link between SST and near-surface atmosphere conditions within the coupled system was discussed by Lewis et al. (2018b) in considering the relationship between near-surface stability and wind speed over the ocean." How this relates to the sentence before? More details or a summary of Lewis et al. (2018a)'s conclusions about the SST/stability/wind relationship would be useful.*

This section has been developed further in the revised manuscript, noting in particular RC2's comment 6 noting this section was too briefly discussed in the original. In summary, we argue that maintaining a feedback between SST, near-surface stability and near-surface winds is required.

• *Tables 2/3: Replace FIX_xx by FOR_xx*

Thank you, this has been corrected in the updated manuscript.

• *Please revise Figure 1: The colour scale for bathymetry in a is blank. What is the 'UKV' atmosphere grid? What are the small black and red points in b?*

The original Figure 1 colour scale in (a) was attempting to reference the contour lines off-shelf. These have now been made thicker in the revised manuscript. The caption text has been updated to clarify what was meant by the 'UKV grid', and the size of symbols referenced in the caption – the small points indicating points where there are a limited number of observations available over the selected period.

• *Figure 2: If possible add the OSTIA SST error time-series.*

Thank you for this suggestion. The comparison between daily OSTIA SST with in-situ observations is now included in the revised Figure 2. The OSTIA SST error has a strong diurnal signal given that it is a daily SST product, but comparisons with in-situ observations are hourly to be consistent with the model vs observation comparison. OSTIA data have also now been used as a reference in the revised Figure 3, and an OSTIA SST time series at the L4 location has been added to the revised Figure 4(a).

• *Figure 6: Please, adjust the colour bars in i, j, k, l.*

Figure 6(i-l) have now been pulled out into a new Figure 6 in the revised manuscript, focussing only on the impact of coupling (CPL_AOW-FOR_HI), with revised colour bars and clearer plots.

• *Figure 7: Add the colour legend for b (which simulation is the blue line?). Larger plots can also help to distinguish more the time-series in c.*

Corrected in revised Figure 7(b), and updated Figure 7 to have larger and clearer plots.

• *Figure 12: "...between 20 and 30 July 2014..."*

Corrected in revised manuscript.

Evaluating the impact of atmospheric forcing~~ resolution~~ and air-sea coupling on near-coastal regional ocean prediction

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Abstract.

Atmospheric forcing applied as ocean model boundary conditions can have a critical impact on the quality of ocean forecasts. This paper assesses the sensitivity of an eddy-resolving (1.5 km resolution) regional ocean model of the North-West European shelf (NWS) to choice of atmospheric forcing ~~resolution~~ and atmosphere-ocean~~air-sea~~ coupling. The analysis is focused on a month-long simulation experiment for July 2014 and evaluation of simulated sea surface temperature (SST) in a shallow near-coastal region to the south-west of the UK (Celtic Sea and western English Channel). Observations of the ocean and atmosphere are used to evaluate model results, with a particular focus on ~~above and below the sea surface at~~ the L4 ocean buoy from the Western Channel Observatory as a rare example of co-located data above and below the sea surface. ~~are used to evaluate ocean and atmosphere model data.~~

The impacts of differences in the atmospheric forcing are illustrated by comparing results from an ocean model run in forcing mode using operational global-scale numerical weather prediction (NWP) data with an ocean model run forced by a convective scale regional atmosphere model. The value of dynamically representing feedbacks between the atmosphere and ocean state is assessed through use of these model components within a fully coupled ocean-wave-atmosphere system.

Simulated SST show considerable sensitivity to atmospheric forcing and to the impact of model coupling in near-coastal areas. A warm ocean bias relative to in-situ observations in the simulation forced by global-scale NWP (0.7 K ~~mean difference, warmer relative to all observations~~ in the model domain) is shown to be reduced (to 0.4 K) through use of the 1.5 km resolution regional atmosphere forcing. When simulated in coupled mode, this bias is further reduced (by 0.2 K).

Results demonstrate much greater variability of both surface heat budget~~energy balance~~ terms and near-surface winds in the convective scale~~higher resolution~~ atmosphere model data, as might be expected. Assessment of the surface heat budget~~energy balance~~ and wind forcing over the ocean is challenging due to a scarcity of observations. It can however be demonstrated that the wind speed over the ocean simulated by the convective scale~~high resolution~~ atmosphere agreed with the limited number of observations less well than the global-scale NWP data. Further partially-coupled experiments are discussed to better understand why the degraded wind forcing does not detrimentally impact on SST results.

1 Introduction

The exchanges of heat and momentum across the air-sea interface are fundamental components of the climate system (e.g. Yu et al., 2012), and can play a significant role in the evolution of natural hazards (e.g. Wada et al., 2018). In oceanography, accurate representation of the surface heat~~energy~~ budget and near-surface winds and momentum fluxes are essential boundary conditions for ocean models given that they drive the ocean energy and dynamics from the surface (e.g. Lellouche et al., 2018). Despite this, routine evaluation of the quality of the surface forcing of operational ocean forecast systems receives relatively little focus. To a large extent, this reflects the challenge of observing these quantities over the ocean compared with on land, and thereby limited availability of measurements for evaluation (Drechsel et al., 2012; Banta et al., 2018). This may also be a result of operational ocean forecast systems running in a 'forced-mode' approach, whereby the surface forcing is provided from an external source of atmosphere model data. Typically the evaluation of atmosphere forecast quality is separated, potentially in science and organisational scope, from research and development of ocean forecast systems. Evaluation of wind forcing for operational wave models has been more prevalent, given the strong sensitivity of wave predictions to their accuracy (Cavaleri et al. 2009).

The development of fully coupled atmosphere-ocean modelling prediction systems provide both motivation and tools with which to better understand the impact of the surface forcing on operational ocean forecasts (e.g. Pullen et al., 2017). This paper discusses an application of a regional coupled system for a North-West European shelf (NWS) domain at km-scale resolution to assess the impact of atmospheric forcing resolution and air-sea feedbacks on the quality of ocean predictions. The study focusses on a near-coastal region ~~given that it is both where populations and critical infrastructure are located and~~ as they represent complex environments where providing accurate predictions can be more challenging through the strong influence of land-sea contrasts on both atmospheric forcing and ocean models (e.g. Holt et al., 2017; Cavaleri et al., 2018).

The role of atmospheric forcing and coupling has been previously addressed at coarser scales in the context of regional climate modelling. For example, Béranger et al. (2010) compared ocean simulations of the Mediterranean forced by atmospheric data provided at horizontal resolutions of about 100 km and 50 km. They found an important influence of the higher resolution wind forcing in particular in driving a more realistic ocean circulation. At increased resolution, Akhtar et al. (2018) showed improved wind speed and turbulent heat flux simulations using a 9 km spacing atmosphere model relative to 50 km more typical of global climate modelling, and both improved by coupling between ocean and atmosphere. It was noted that radiation fluxes were slightly better represented at the coarser resolution however, due to poorer representation of cloud cover in the 9 km resolution simulations.

An evaluation of the influence of surface fluxes on regional ocean simulations of the Mediterranean Sea was also assessed by Lebeaupin Brossier et al. (2011), who found that improving the temporal resolution of the atmospheric forcing, as well as the spatial resolution over some coastal areas, significantly changed the variability of mesoscale ocean processes. In regions where increased resolution enhanced near-surface winds, ocean convection was shown to be increased, although when applying higher frequency forcing the convection was dampened through changes to ocean stratification. Schaeffer et al. (2011)

demonstrated improved representation of ocean eddies in the Gulf of Lion with a change from 9 km to 2.5 km resolution wind forcing, but little impact of temporal resolution. Of relevance to the NWS, Bricheno et al. (2012) found a reduction on wind speed errors of more than 10% when moving from use of a 12 km to 4 km resolution atmosphere forcing for a wave-ocean coupled system of the Irish Sea.

A number of studies using a range of km-scale regional coupled systems more typical of the scale of current operational ocean forecast systems have reported that simulated atmospheric fluxes can be improved through representing air-sea interactions (e.g. see Pullen et al., 2017 for a review~~Lewis et al., 2018a~~). For example, Carniel et al. (2016) and Licer et al. (2016) assessed the impact of coupling on components of the surface heat~~energy~~ budget for different coupled simulations of the Adriatic Sea, and showed that much improved turbulent heat fluxes resulted in improved predictions of sea surface temperature (SST) relative to forced mode ocean simulations. Similar sensitivity was demonstrated by Bruneau and Toumi (2016) for the Caspian Sea. Gronholz et al. (2017) showed improved SST prediction for the North Sea through use of a higher resolution regional atmosphere forcing rather than a global-scale analysis, and further improvement through coupling between atmosphere and ocean. The influence of improved wind forcing through wave-atmosphere coupling was demonstrated by Wahl et al. (2017) for a similar domain.

The implications of the choice of atmospheric forcing~~ resolution~~ and air-sea coupling on ocean forecasts for the NWS are assessed in this paper using the UKC3 regional coupled system. Lewis et al. (2018b) described the system in detail and provided an initial domain-wide assessment of the UKC3 ocean performance for month-long simulations in four different seasons. This study focuses on near-coastal results for one of those periods in July 2014. The focus on the July 2014 results in this paper is motivated by Lewis et al. (2018b) having identified the impact of coupling on SST simulations to be greatest during summer. The focus here on assessing the near-coastal response in particular is also in contrast to the overview of results from atmosphere, ocean and wave components across the whole domain described by Lewis et al. (2018b) to summarise the overall system performance. A further limitation of the initial discussion by Lewis et al. (2018b) arises from their comparison of coupled results with control simulations designed to be most analogous to the current approach adopted in operational systems. For the ocean model, differences between coupled results and the ocean-only control run forced by global-scale NWP may arise both from representing air-sea interactions and from the scale and characteristics of the atmospheric forcing differing between the two configurations. An additional uncoupled control simulation is therefore introduced in this study in which the regional ocean model is forced by the higher resolution convective scale regional atmosphere model forcing, but without feedbacks between atmosphere and ocean. Further details on ~~T~~the application of UKC3 in the current study is described in Sect. 2. Simulated SST and the different atmosphere forcing are compared with available in-situ measurements in Sect. 3 and conclusions drawn in Sect. 4.

2 Methods

2.1 Ocean model configurations and atmospheric forcing

This study makes use of the AMM15 (Atlantic Margin Model, 1.5 km horizontal grid resolution) ocean model configuration, as described in detail by Graham et al. (2018), and in use for operational oceanography across the North-West European shelf (NWS) within the Copernicus Marine Environment Monitoring Service (CMEMS; Tonani et al., 2019~~8~~, *this issue*). AMM15 uses the NEMO ocean model code (vn3.6_STABLE, r6232; Madec et al., 2016). The model domain is illustrated in Fig. 1(a), which shows~~ing~~ the relatively shallow North-West European shelf and shelf-break bounding to the North Atlantic to the west. The forced mode and coupled implementations evaluated in this paper were documented in detail by Lewis et al. (2018b).

A number of forced and coupled simulations spanning a month-long period between 30 June and 31 July 2014 have been conducted. To highlight ocean model performance in a near-coastal environment, the subsequent analysis focusses on evaluation relative to in-situ observations over the ocean within a section of the model domain encompassing the Celtic Sea and surrounding south-western approaches to the UK (Fig. 1(b)). The on-shelf part of this region has water depths of order 50 to 100 m and is seasonally stratified from late-April until September and well mixed through the rest of the year.

A summary of the four simulation experiments considered is given in Table 1. All ocean simulations were initialised from the same initial condition, taken from the 30-year free-running AMM15 simulation documented by Graham et al. (2018). As described by Lewis et al. (2018b), the same lateral boundary conditions using ocean model output from the coupled GloSea5 seasonal prediction system at 1/4° horizontal resolution (MacLachlan et al., 2015) were applied in all simulations. The same climatological freshwater discharge data were also applied to all simulations (Graham et al., 2018). All experiments are conducted in forecast mode without data assimilation in any regional components.

Experiments FOR_GL and FOR_HI are forced mode ocean model simulations, in which externally generated atmospheric forcing~~meteorological data~~ a~~we~~re applied via file input. This is the approach most typically used in operational ocean forecast systems (e.g. Tonani et al., 2019~~8~~, *this issue*). In forced mode~~this study~~, variables describing the surface heat~~energy~~ and water budget and near-surface wind computed on an external atmosphere model grid are applied as a surface boundary condition in NEMO using the 'flux formulation' methodology (Madec et al., 2016). The wind stress is computed in NEMO from the 10 m wind speed forcing, based on Smith and Banke (1975). The FOR_GL and FOR_HI runs contrast in the spatial scales and temporal resolution of atmospheric~~meteorological~~ information applied. In FOR_GL forcing data originating from a global-scale operational weather forecast using the Met Office Unified Model (MetUM) are interpolated onto the 1.5 km resolution ocean grid. For the period considered in this paper, the global MetUM forecast system used the Global Atmosphere (GA) and Global Land (GL) version 6.1 science configurations, documented in detail by Walters et al. (2017a). Across the NWS, global data from this system were available at a horizontal spatial resolution of about 17 km, with radiation variables applied at 3 hourly and wind components at hourly intervals through the simulation. The ocean surface boundary condition in the global MetUM is provided by the daily OSTIA (Operational Sea Surface Temperature and Sea Ice Analysis; Donlon et al., 2012).

Surface currents are assumed zero and a constant global value for the ~~wave-dependent roughness~~ Charnock parameter of 0.085 is used.

By contrast, FOR_HI is forced by variables interpolated from a regional atmosphere configuration of the MetUM, equivalent to that used for regional-scale operational weather prediction at the Met Office (RA1; Bush et al., 2018). The regional atmosphere configuration has a variable resolution grid (Tang et al., 2013), with a region of regularly spaced cells across the UK at 1.5 km horizontal spacing (Fig. 1(a)), and stretching out to 1.5 km x 4 km cells towards the domain boundaries. The regional atmosphere domain extent matches that of the regional ocean configuration (Lewis et al., 2018b). At this atmosphere model resolution convection is explicitly resolved and local details such as the model coastlines and orography impact on the meteorology (e.g. Clark et al., 2016). All atmospheric~~meteorological~~ data from this convective-scale~~e~~ km-~~high~~ resolution system were applied to the ocean at hourly frequency. For the month-long regional atmosphere simulation considered here, the surface boundary condition to the atmosphere model~~simulation~~ was also provided by interpolation from the daily OSTIA, and kept constant for each 24 h period. As in the global NWP system, ocean surface currents are assumed zero and ~~but~~ a constant value for the Charnock parameter of 0.011 is now assumed. Details of the RA1 regional MetUM configuration, and how they relate to the global-scale NWP configuration, are provided by Bush et al. (2019~~8~~). One of the key differences, related to the horizontal grid resolution is that atmospheric convection is explicitly represented in FOR_HI, whereas its simulation is parameterised in FOR_GL. The treatment of solar and terrestrial radiation also differ between RA1 and GA6.1 configurations. The RA1 configuration is most analogous to that used in GA7, which has an improved treatment of gaseous absorption compared to GA6 which typically result in reduced clear-sky outgoing long-wave radiation and increased downwards surface flux (Walters et al., 2017b). A final key difference between the global and regional MetUM configurations is that the parameterisation of clouds in FOR_GL uses the PC2 prognostic scheme (Wilson et al., 2008) and in FOR_HI uses the Smith (1990) diagnostic cloud scheme. One advantage of the prognostic approach is that clouds can be advected away from where they were created, but the diagnostic scheme is still considered to provide better forecasts in mid-latitude regional atmosphere configurations (Bush et al., 2018).

Coupled experiments CPL_AO and CPL_AOW use the AMM15 ocean model configuration as part of the UKC3 dynamically coupled system (Lewis et al., 2018b). The MetUM atmosphere model component is the same as used in atmosphere-only mode to provide FOR_HI forcing (i.e. 1.5 km variable resolution grid and RA1 science configuration), but now coupled directly to the ocean using the OASIS3-MCT (Craig~~Valcke~~ et al., 2017~~5~~) libraries with all information exchanged at hourly frequency. The CPL_AO simulation involves only atmosphere and ocean components being coupled – with heat budget terms, surface wind stress components and the surface pressure field passed from atmosphere to ocean components, and the simulated SST and currents passed from ocean to atmosphere. The ‘fully coupled’ CPL_AOW simulation also incorporates coupling between both atmosphere and ocean models to the WAVEWATCH III (Tolman et al., 2004) spectral wave model, defined on the same model grid as AMM15. Additional exchanged variables in CPL_AOW include the wind forcing from atmosphere to wave, the Charnock parameter from wave to atmosphere, water level and currents from ocean to wave, and significant wave height, Stokes drift components, and wave-modified surface drag from wave to ocean model components.

2.2 In-situ observations and the Western Channel Observatory

Atmosphere and ocean model simulations~~ from these experiments~~ are compared to in-situ observations obtained from the operational network of surface automatic weather stations, ships and drifting or moored ocean buoys that are routinely exchanged in near real-time over the World Meteorological Organization Global Telecommunication System (GTS). A representative distribution of the location of these sites across the Celtic Sea sub-region is shown in Fig. 1(b). In this study, model data~~simulations~~ are compared with point observations by considering a mean of model output in the 5 x 5 neighbourhood of grid cells nearest to a given observation site. While this will smooth out some of the very fine resolution detail evident in AMM15 ocean simulations.~~,~~ However it~~this~~ is considered a more representative approach than using only the nearest grid cell to reduce the 'double penalty' effects common with evaluating high resolution atmosphere or ocean model results~~simulations~~ for which a slight spatial or temporal displacement in the prediction of resolved small scale features relative to observations can lead to apparent relative errors at both observed and simulated locations, although the characteristics of such features may be well captured (e.g. Mass et al., 2002).

Around the southern UK coasts, most routine ocean observations are provided by the WaveNet monitoring network (Centre for Environment, Fisheries and Aquaculture Science; Cefas, http://wavenet.cefas.co.uk) and the Channel Coast Observatory (http://www.channelcoast.org). A number of these in Fig. 1(b) are sites where SST and near-surface wind observations are co-located. Figure 1(b) also highlights how the majority of ocean observing sites are located within only a few kilometres of the coast, and are therefore most representative of near-coastal conditions.

This study also uses atmosphere and ocean observations from a number of different sensors co-located at the L4 site of the Western Channel Coast Observatory (WCO; Smyth et al., 2010. See also https://www.westernchannelobservatory.org.uk). L4 is located at 50° 15′N, 4° 13′W, about 6 km away from the southern England coast, where the sea is about 50 m deep. A variety of long-term records of physical ocean, atmosphere and marine biogeochemical observations are recorded at L4 (Smyth et al., 2014). Of interest here are the in-situ surface and depth profile temperature measurements from a CTD, air temperature and wind speed measurements, and total and diffuse solar radiation measurements within the 400 – 2700 nm wavelength range using a SPN1 Sunshine Pyranometer.

3 Results

3.1 Domain-wide sea surface temperature (SST)

Figure 2 summarises the mean difference between ocean model SST and in-situ buoy observations across the AMM15 domain (e.g. see Fig. 1(b) of Lewis et al. (2018) for locations) during July 2014. Also shown is the equivalent comparison between daily OSTIA (Operational Sea Surface Temperature and Sea Ice Analysis; Donlon et al., 2012) and in-situ observations. Statistics of the mean difference (MD) and root mean square difference (RMSD) relative to all observations across the month are listed in Table 2. Figure 2 highlights~~demonstrates~~ that all ocean simulations had a common~~the same~~ initial condition, which for this case was on average about 0.8 K warmer than observed. A summer time warm bias relative to OSTIA was noted by Graham et al. (2018). This warm difference is maintained throughout the month for the FOR_GL simulation, with MD over the month of 0.73 K. This is consistent with the AMM15 run used to provide the initial conditions also being forced with a global-scale meteorology and being a well spun-up ocean state (Graham et al., 2018), so that the bias inherited from the initial condition is maintained. By contrast, the mean difference is substantially reduced comparing FOR_HI to observations (MD = 0.40 K), with FOR_GL and FOR_HI results diverging within the first few days of the simulation. This indicates ~~improved~~ SST prediction ~~can be achieved~~ for the NWS is sensitive to the choice of ~~when applying the high resolution~~ meteorological forcing.

Further reduction of the SST bias seen in Fig. 2 when considering coupling between the regional~~high resolution~~ ocean and atmosphere models in CPL_AO (MD = 0.26 K). There is some additional value evident from coupling information of the wave state to ocean and atmosphere components in CPL_AOW (MD = 0.20 K), although this is of secondary importance to the impact of either changing the source of atmosphere forcing~~resolution~~ or ocean-atmosphere coupling for this period and location.

3.2 SST in the Celtic Sea

To further examine the sensitivity highlighted in Fig. 2, the remaining analysis focuses on results across the Celtic Sea region only, and considers simulation results over the 10-day period between 20 July and 30 July 2014, as being representative of the different ocean simulations having spun up sufficiently from the same initial condition. This is supported by the summary statistics considering only this region and period listed in Table 2, from which broadly consistent conclusions can be drawn as from the statistics obtained for the full domain and simulation duration. In this case, the MD for CPL_AOW is 1 K smaller than that for FOR_GL results, and the RMSD is reduced from 1.6 K to 1.0 K.

A snapshot comparison~~illustration~~ of SST across the Celtic Sea on 28 July 2014 from FOR_GL and FOR_HI simulations with OSTIA show qualitatively very consistent patterns (Fig. 3(a) and 3(b)). These snapshots are representative of the 10-day mean differences shown in Fig. 3(d) and 3(e). ~~, with a~~Areas of relatively cooler water are simulated around west-facing peninsulas such as the Ushant front region to the west of Brittany, and around south-western England. Simulated SST across much of the Celtic Sea is relatively cooler in FOR_HI than FOR_GL however, in closer agreement with OSTIA overall. Both simulations have warmer surface water in near-coastal regions than observed, such as in the Bristol Channel where the simulated SST exceeds 294.5 K on 28 July.

Instantaneous and 10-day mean SST from the coupled CPL_AOW simulation are shown in Fig. 3(c) and 3(f) respectively. There is ~~The mean impact of coupling on SST is shown in Fig. 3(c) as an average across the 10 day period. This shows~~ an extensive region where SST is reduced by more than 0.5 K across the Celtic Sea. While differences are lower through the English Channel, stronger relative cooling is also apparent along the coastlines of southern Wales, within the Bristol Channel, and around the Isle of Wight to the east of the domain section. In general, the CPL_AOW results are in closer agreement with OSTIA (Fig. 2), although there is some compensation between the coupled model being relatively cooler in more open ocean and warmer in near coastal areas. Figure 3(g)-(i) compares the RMSD over 10 days for each simulation with in situ observations relative to the RMSD between OSTIA and observations at each site. This highlights the relatively poor agreement of FOR_GL results (Fig. 3(g)) but ~~There is qualitatively improved agreement of simulated SST with coastal observations across the region for CPL_AOW, with~~ relative improvements in RMSD for CPL_AOW results by in excess of 20 % at all near-coastal observing sites (Fig. 3(i)~~4~~).

SST results at L4 between 20 and 30 July 2014 are shown in Fig. 4~~5~~(a). At this location, the coupled experiments are cooler than observed, although the lowest RMSD (of 0.5 K) is obtained for CPL_AOW. The SST observations at L4 during late July 2014 were highly variable, with an observed range of 4 K shown in Fig. 4~~5~~(a). On several days (e.g. 20, 21, 23, 26 and 29 July) a tidally-dominated~~forced~~ heating signal of about 1 K is apparent. This was particularly strong on 22 and 25 July ~~however~~, potentially linked to strong solar heating in additional to tidal influence, when a range of 2 K and 3 K were observed respectively. More synoptic-scale influences appear to dominate on 27 and 28 July when the observed SST cycle was relatively diminished. The temporal ~~SST~~ variability of SST at L4 for ~~of~~ FOR_GL is in general larger on diurnal timescales~~stronger~~ than observed, but reasonably well captured by all other ocean simulations with high-resolution atmosphere forcing (Fig. 4(a)). This is not the case on 25 July however, when the increase in FOR_GL temperature through the day matches the observed range, while all other simulations fail to replicate such strong temperature variation.

In addition to surface measurements, depth resolved temperature data are routinely taken using CTD sensors at the L4 site on days when data are manually collected. One such profile was observed during the morning of 28 July 2014, and is compared with daily mean simulated temperature profiles at L4 in Fig. 4~~5~~(b). The observed profile shows a strong temperature gradient between depths of 10 m and 15 m marking the mixed layer depth (MLD), with well mixed water near the surface and stratified water below to the sea bed. There are substantial differences between the simulated profiles in Fig. 4~~5~~(b). The excessive surface heating in FOR_GL can be attributed to a much shallower MLD than observed, such that any input solar heating at the surface will heat a smaller volume of water than in reality. In contrast, the near-surface temperature and MLD is in good agreement with observations on this day in the FOR_HI simulation with high resolution atmospheric forcing. The strength of cooling across the thermocline is considerably less sharp than observed (or in FOR_GL), although this may be partly an artefact of using a daily mean rather than instantaneous profile and of averaging simulation results across a 5 x 5 neighbourhood of grid cells. Mean temperatures from FOR_HI are order 1 K warmer than observed between the MLD and a depth of about 35 m. This mean difference is improved when the ocean and atmosphere are coupled (CPL_AO), reflecting a positive impact of representing air-sea interactions within the system both at (Fig. 4(a)) and below the surface (Fig. 4(b)). An improved temperature profile at L4 below the mixed layer in the fully coupled CPL_AOW simulation is offset by a cool surface bias, leading to a relatively weaker temperature transition than in CPL_AO. Further tuning of the CPL_AOW system may be appropriate, as discussed by Lewis et al. (2018c, *this issue*).

These results demonstrate that SST and temperature profiles through depth are particularly sensitive to the source of atmospheric forcing ~~resolution~~ and to representation of air-sea interactions across the NWS, with fundamental differences in the vertical structure developing between simulations from a common initial condition over a relatively short period of time.

3.3~~2~~ Surface heat~~energy~~ budget

The ocean surface boundary condition characterising the heat ~~energy~~ budget in NEMO is expressed in terms of the solar radiation, Q_{SW}, that penetrates the top few metres of the ocean, and a non-penetrative component, Q_{ns}, which only heats or cools the surface (Madec et al., 2016). In the AMM15 configuration, Q_{SW} specifies the net shortwave radiation at the surface simulated by an atmosphere model across all wavelengths, and Q_{ns} is computed from the surface heat~~energy~~ budget variables as,

$$Q_{ns} = Q_{LW} - \lambda E - H, \tag{1}$$

with Q_{LW} denoting the net surface longwave radiation, λE the latent heat due to evaporation and H the sensible heat flux. In NEMO, the fraction of Q_{SW} which penetrates to lower depths is controlled by the *rn_abs* parameter. In the simulations considered in this study, it is assumed that 66% of radiation is absorbed at the surface (Lewis et al., 2018b).

The spatial distribution of Q_{SW}, Q_{LW}, λE and H used as forcing for FOR_GL (i.e. interpolated from the global-scale operational MetUM) is shown as 10-day means in Fig. 5, together with the mean difference between~~,~~ FOR_HI (i.e. interpolated from the variable resolution regional atmosphere simulation) and FOR_GL.~~and from CPL_AO and CPL_AOW coupled systems are illustrated in Fig. 6. Snapshots of the forcing at 1200 UTC on 28 July 2014 show a typical daytime distribution.~~ The magnitude of mean net solar short-wave radiation of order 250~~800~~ Wm^{-2} (Fig. 5~~6~~(a)~~(e)~~) clearly dominates the heat budget relative to the net long-wave radiation (of order 50~~70~~ Wm^{-2} away from the surface, Fig. 5~~6~~(b)~~(f)~~) and sensible heat flux (mean 5~~10 to 20~~ Wm^{-2} away from the surface across the Celtic Sea, Fig. 5~~6~~(c)~~(g)~~). The latent heating over the ocean is also shown to be a relatively important contribution to the surface energy balance, with a mean of order ~~values up to 1~~50 Wm^{-2} in FOR_GL forcing~~simulated~~ (positive values indicating a flux of heat to the atmosphere from evaporation of sea surface water). Comparing the spatial distribution of FOR_HI~~GL~~ and FOR_GL~~HI~~ heat budget terms in Fig. 5(e)-(h)~~6~~ shows generally close agreement on the large-scale (noting the scale of differences relative to the flux magnitudes), particularly for the sensible and latent heating which are driven by near-surface variability, although the magnitude of latent heating in FOR_HI is larger than FOR_GL. A key difference is the reduced mean solar radiation Q_{SW} in FOR_HI relative to FOR_GL by more than 25 Wm^{-2} across the Celtic Sea (Fig. 5(e), and reduced long-wave radiation loss away from the surface (Fig. 5(f)). The local scale variability of heating is also substantially greater in FOR_HI ~~(e.g. Fig. 6(e))~~ than FOR_GL ~~(Fig. 6(a)) however~~, as might be expected given the contrast in atmosphere model resolutions and representation of convection. An imprint of a pattern of convective cells can be seen in the FOR_HI forcing differences for example, which likely leads to highly variable heating in time.

The spatial distribution of time mean differences between CPL_AOW and FOR_HI heat~~energy~~ budget terms between 20 and 30 July 2014 are ~~also~~ shown in Fig. 6. The impact of coupling on Q_{SW} and Q_{LW} is dominated by random changes in the spatial distribution of convection (Fig. 6(a~~i~~),(b~~j~~)). Examination of the simulated cloud fields during this period (not shown) indicate substantial changes in the exact spatial distribution of clouds at any given time between FOR_HI and CPL_AOW for example. The clearest relative impact of air-sea coupling is on the latent heat flux, which is broadly reduced by order 20% across the

Celtic Sea in CPL_AOW. There is also some evidence that the latent heat flux is increased in ~~those~~ near-coastal regions in CPL_AOW relative to FOR_HI. This coincides with regions of cooler SST ~~identified as being cooler~~ in CPL_AOW than FOR_HI (Fig. 3), and~~where the coupled simulation SST was~~ in closer agreement with in-situ observations ~~in Fig. 3(c)~~.

The sunshine pyranometer sensor at L4 provides a rare source of observations of the solar radiation over the ocean (Fig. 7(a)). The raw measurements at 1 min sampling frequency have not been corrected for wave motion, which can lead to considerable variability, particularly when the sea state increases. The data shown in Fig. 7(a) are hourly mean values and therefore considered as being representative. The total observed solar radiation exceeds 800 Wm^{-2} on several days between 20 and 30 July 2014, particularly on 20 – 23 July, but increased cloud cover on 24 July leads to the most of the observed radiation coming from the diffuse component at L4. Given that the observations cover the wavelength range 400 – 2700 nm, these are not directly compared with the atmosphere model data. The time series of simulated Q_{SW} across all wavelengths at the L4 location (Fig. 7(b)) shows broad agreement however. On most days, the simulated peak in short-wave flux at L4 differ between the sources of atmosphere data considered within 100 Wm^{-2} and with FOR_GL typically lower than the regional atmosphere ~~high resolution~~ data. ~~This could be related to~~ T~~t~~he different temporal resolution of the data, with~~and~~ the 3 h updates of FOR_GL being insufficient to adequately capture the daytime maximum, is a possible explanation for the difference. The warm surface temperature bias of FOR_GL at L4 is therefore not readily explained by assessing the local radiation budget in the immediate vicinity ~~appears to result despite rather than because of this difference however~~. The global- and regional-scale ~~and high resolution~~ data ~~are very~~ differ~~ent~~ more on 24 July, when FOR_GL has much lower Q_{SW}, in good qualitative agreement with the L4 observations (Fig. 7(a)). The FOR_HI and coupled simulations all have a strong diurnal variation in contrast on this day. Despite this, the rate of simulated SST change at L4 in Fig. 4~~5~~(a) on this day was generally consistent across each simulation, suggesting this to be mostly tidally-driven rather than a result of local heating. Time series of the non-penetrating heat budget term Q_{ns} are shown at L4 is shown in Fig. 7(c). Values typically agree within 50 Wm^{-2} between experiments through the period, although it is interesting to note that FOR_HI data are more variable than either the global-scale FOR_GL forcing or the coupled system results.

Although it is particularly challenging to routinely measure all components of the surface heat~~energy~~ budget over the ocean (Yu et al., 2012), the availability of both air and surface temperature observations at L4 enables at least some comparison of the near-surface stability profile (air – surface temperature) against the high-resolution atmosphere simulations (Fig. 7(d~~c~~)). The magnitude of the observed diurnal variability is in general well captured by all simulations, although air-sea coupling appears to correct periods on 22, 23 and 29 July when the FOR_HI regional atmosphere simulation has surface temperature too warm relative to air temperature, which cause spikes in sensible heat flux that are reflected in the Q_{ns} comparisons (Fig. 7(c)~~(not shown~~).

Taking a broader perspective of the surface heat budget~~energy balance~~ across all sea areas in the Celtic Sea sub-region shows the net effect of the different atmosphere forcing and air-sea coupling (Fig. 8). In Fig. 8(a)-(c)~~Here~~, variables are accumulated ~~averaged~~ across all model grid cells over sea in the region and time series of the spatial standard deviations shown in Fig. 8(d)-(f). In contrast to Fig. 7(b) for the L4 site, the accumulated net radiation (sum of short-wave and long-wave) across the whole region in Fig. 8(a) shows more consistently increased net radiation in the FOR_GL data. On 22 July 2014 for example, the mean daytime maximum net radiation (not shown) is over 150 W m^{-2} higher in FOR_GL than the high resolution data. Values are also consistently higher during night time in the global-scale ~~resolution~~ forcing data. These differences are reflected in a mean net radiation flux over the 10 days shown of 244 W m^{-2} in FOR_GL compared with 227 W m^{-2} in the CPL_AOW simulation. The mean net radiation for the Celtic Sea is order 7% higher in FOR_GL data than any of the regional-scale~~high resolution~~ runs. This difference is consistent with the warm SST bias of FOR_GL relative to FOR_HI or coupled ocean simulations being driven by a relatively higher net radiation when using the global-scale atmospheric forcing relative to the regional scale. Figure 5~~6~~ illustrates the FOR_GL simulated heat budget terms ~~radiation~~ to be ~~a~~ relatively smooth fields while high variability of radiation between convective cells in FOR_HI and coupled simulations is thought to produce small scale ~~patches~~areas of ~~where~~ relatively reduced heating which contribute to the reduced short-wave radiation flux shown in ~~(~~Fig. 5~~6~~(e~~a~~) for example~~)~~. Some evidence of this is apparent in the time series of net short-wave radiation at L4 on 28 July 2014 in Fig. 7(b). The effect of different atmosphere forcing and coupling ~~resolution~~ is also highlighted through considering the standard deviation of net surface radiation across the region (Fig. 8(d)~~not shown~~). A summary of these results is given in Table 3, which shows that daytime maximum values in excess of 250 W m^{-2} are calculated using either FOR_HI or coupled results. In contrast, the standard deviation of the FOR_GL radiation data are consistently lower during both day and night and with a maximum standard deviation of less than 200 W m^{-2}, but typically of order 20-50% lower than high resolution atmosphere simulation values (Fig. 8(d)). ~~This provides some evidence that the differences between the representation of the surface energy budget in the global and regional-scale atmosphere simulations is driven mostly by the change in grid resolution and the change from parameterised to explicitly represented convection, rather than from differences between the underpinning MetUM radiation and cloud parameterisation choices, which might be expected to principally drive differences in the mean conditions rather than the spatial variability.~~

T~~t~~he accumulated non-penetrating radiation term, Q_{ns}, (Eq. (1)) across the Celtic Sea (Fig. 8(b)) shows much smaller net differences between experiments than for Q_{SW}. Time series of the spatial standard deviation of ~~non-penetrating radiation term,~~ Q_{ns} ~~(Eq. (1)),~~ across the region in Fig. 8(e)~~at L4 (not shown)~~ also demonstrate ~~much~~ greater variability for the regional-scale~~high resolution~~ forcing, and larger ~~substantial~~ differences between FOR_HI and the coupled simulations (with CPL_AO and CPL_AOW being more~~quite~~ consistent with each other). ~~Considering~~ ~~the accumulated Q_{ns} across the Celtic Sea (Fig. 8(b)) shows much smaller net differences between experiments than for Q_{SW}.~~ The difference between global and regional-scale time series on 27 – 29 July can be attributed to the sensitivity to latent heat flux (Fig. 8(c)). The reduced latent heating due to coupling during this period also results in a less strong upward (i.e. less negative) Q_{ns} for coupled results relative to FOR_HI in Fig. 8~~7~~(b). Lebaupin Brossier et al. (2015) assessed the role of atmosphere-ocean coupling on the water budget of the Mediterranean simulated using a 20 km resolution regional atmosphere and 1/12° ocean model components, with SST found to be a key controlling factor of evaporation. This link can also be clearly seen in the Celtic Sea by the clear spatial similarity between the impact of coupling on latent heating in Fig. 6(d) with the difference between the mean CPL_AOW SST field and OSTIA in Fig. 3(f) – noting that OSTIA data were used as the SST boundary condition driving the FOR_HI atmosphere simulations.

In summary, the key sensitivity of~~for~~ the regional ocean simulations~~forecasting~~ to~~of~~ differences in the surface heat budget~~energy balance~~ from different sources of atmospheric ~~meteorological~~ forcing is dominated by~~in~~ the representation of the net short-wave radiation. A second-order but non-negligible differences in the latent heat flux is also found, linked to the different representation of SST in atmosphere simulations. When using a global-scale atmosphere forcing~~simulation~~, as typical for most operational ocean forecast systems, the high spatial variability associated with convection is not captured, which leads to a larger accumulated heating over a given region in this case. Applying a more spatially variable representation of the surface heat~~energy~~ budget when using~~applying~~ the regional-scale~~using high-resolution~~ forcing (FOR_HI) or atmosphere-ocean coupled systems (CPL_AO or CPL_AOW) contributed~~led~~ to the improvement to the warm SST bias found in the FOR_GL ocean simulation.

3.4~~3~~ Near-surface wind speed

Snapshots of the global-scale and high-resolution regional atmosphere model wind speed at 10 m above the surface in Fig. 9 also reflect the much finer convective structures simulated in the FOR_HI simulations (Fig 9(b)). The general structure of wind speed available from the operational global-scale MetUM atmosphere model (Fig. 9(a)) is in qualitative agreement with in-situ observations at this time, particularly in reflecting areas of reduced wind speed across the Bristol Channel and off the southern England coast. The observations over sea are spatially more variable than FOR_GL across the region however. In contrast, the FOR_HI data show an area of strong convective activity over the Celtic Sea, and the spatial variability of wind speed over the ocean qualitatively appears to be as high as over land (Fig. 9(b)). The impact of coupling, quantified as the mean difference over the 10-day period between 20 and 30 July 2014 (Fig. 9(f)), shows wind speed differences of ±0.5 ms^{-1}, largely focused in the English Channel rather than Celtic Sea. ~~The contrast between the spatial variability of wind speed between FOR_GL and FOR_HI further supports the assessment in Sect. 3.2 that the change in surface energy budget characteristics between the different sources of forcing were driven more by the change in atmosphere grid resolution than by changes to the underpinning model physics.~~

The atmospheric~~ocean~~ forcing and coupled results are compared with near-surface wind speed observations at L4 in Fig. 10(a). This shows results typical of that found at other sites in the region (Fig 10(b)) and more generally from analysis of a number of case studies by Lewis et al. (2018a, 2018b) for example. FOR_GL data follow the day-to-day variability of observed wind speed closely (MD = -0.07 ms^{-1}, RMSD = 1.29 ms^{-1}). By contrast, all high resolution experiments are biased fast (e.g. MD = 1.4 ms^{-1} for CPL_AOW) and with increased RMSD relative to observations (Fig. 10(b)). The high temporal variability of wind speed also appears to exceed the observed variability. Figure 11 summarises the mean and range of differences between the global-scale forcing and CPL_AOW simulations relative to all observations across the Celtic Sea region. The wind speed bias in CPL_AOW (and other regional atmosphere~~high resolution~~ data, not shown) becomes particularly high on 27 July. The summary metrics indicate that both CPL_AO and CPL_AOW simulations have reduced differences to observations than

FOR~~FIX~~_HI during the period, although the influence of wave coupling feedbacks is generally small at this time of year. Figure 11(c) and Table 3 summarise~~s~~ the enhanced wind speed variability with increased model resolution in terms of the standard deviation of values across the Celtic Sea region for the regional scale data relative to FOR_GL.~~each simulation.~~

Given the strong sensitivity of surface waves to the near-surface winds, the different characteristics of simulated winds between global and regional-scale systems has been found to have a detrimental impact of the quality of wave model simulations when forced with high-resolution data (Lewis et al., 2018a). As demonstrated in Fig. 10(a), this can be mitigated to some extent through coupling, but it remains challenging to improve the quality of wave forecasts relative to a system with global-scale forcing.

3.5~~4~~ Partially coupled sensitivity experiments

Further work is clearly required to better understand and improve the quality of near-surface winds in the regional atmosphere model. It is therefore of interest to note that the quality of SST from the FOR_HI and coupled ocean simulations was improved relative to FOR_GL, perhaps despite the change in wind speed characteristics.

Two additional ocean-atmosphere coupled simulation experiments have therefore been conducted to further assess the impact of the heat~~energy~~ budget and wind speed forcing changes on the ocean simulation. In pCPL_WIN, only the wind speed components are coupled between the atmosphere and ocean, and radiation variables read from the operational global forcing. In pCPL_RAD, only the radiation variables are coupled and the global-scale wind speed forcing is used. In both simulations, the exchange of variables and feedback from the ocean to the atmosphere was the same as in CPL_AO. Note that these partially coupled simulations are conducted to help attribute the relative impact of energy balance and near-surface wind forcing contributions to the ocean model performance, rather than suggesting these to be valid configurations for operational oceanography in themselves.

The summary results in Fig. 12 shows that SST is improved in pCPL_RAD (MD = 0.76 K, RMSD = 1.18 K) relative to FOR_GL, and has similar performance to FOR_HI during daytime in particular. This shows some benefit of using the regional scale source of heat budget information and global-scale wind forcing. The quality~~improvement~~ of SST results is lower~~not as large~~ for pCPL_RAD than~~as found~~ when coupling both radiation and wind speed in CPL_AO however. This~~,~~ highlights~~suggesting~~ that ensuring that the ocean state is~~properly~~ in balance with the atmosphere is also important,~~.~~ requiring that the near-surface winds are consistent with the near-surface stability driven by air-sea temperature differences for example. Some evidence of the relationship~~link~~ between SST and near-surface atmosphere conditions within the coupled system used in this study was discussed by Lewis et al. (2018b; see their Figure 14). In accordance with the review of Small et al. (2008) for example, they described how an increase in SST through ocean-atmosphere coupling in the NWS can produce less stable near-surface conditions, which can increase near-surface wind speeds (and vice-versa). Meroni et al. (2018) more formally quantified the spatial correlations between mesoscale SST and wind speed variability at high resolution in the Gulf of Lion, which in turn was shown to impact on the distribution of heavy rain bands. The use of an external source of wind forcing in the partially coupled pCPL_RAD experiment here ‘breaks’ any such near-surface stability-wind feedback, and seems to reduce the quality of SST results relative to the fully coupled simulations CPL_AO and CPL_AOW. ~~in considering the relationship between near-surface stability and wind speed over the ocean.~~

The quality of simulated SST is markedly reduced in pCPL_WIN (MD = 1.96 K, RMSD = 2.56 K). ~~however, which~~ This demonstrates the combined detrimental impact of applying a relatively coarse-scale description of the surface radiation budget originating from a global-scale atmosphere and~~,~~ highly variable and biased surface winds originating from the~~a~~ ~~high-resolution~~ regional atmosphere simulation. In addition, ~~and~~ the ocean and atmosphere are no longer~~t~~ ~~being~~ in balance through use of the mixed coupling approach with incomplete representation of feedbacks. This result also confirms that the improvement in SST found in FOR_HI relative to FOR_GL is driven predominantly by the differences to the surface heat~~energy~~ budget ~~forcing~~ between the two sources of atmospheric forcing.

4 Conclusions

This paper has demonstrated that simulation of ocean temperature for the NWS is sensitive to the atmospheric forcing at the surface. Better agreement of simulated SST with observations has been found for a near-coastal environment through use of information from a convective-scale ~~high~~ resolution regional atmosphere simulation rather than using data from a global-scale NWP forecast as applied in most current operational ocean forecast systems.

A key difference in the insolation in the global and ~~convective~~ regional-scale ~~NWP~~atmosphere models comes from the explicit representation of convective clouds and their impacts on radiation. In addition to the increased spatial variability from the regional-scale~~convective scale~~ atmosphere simulations, a mean reduced Q_{SW} of order 7% across the Celtic Sea region has been found compared to the global-scale forcing. In these simulations, which had a positive SST initial bias, this reduction contributed to improved SST prediction.

The near-surface winds also differ between the global NWP and ~~high-resolution~~ regional-scale atmospheric simulations both in the mean and their variability. The regional atmosphere model~~high-resolution~~ winds compare less well to the limited number of observations over the ocean. It is therefore concluded that the impact of wind forcing is of second order to the treatment of insolation on the quality of SST results.

The SST bias in near-coastal areas is further reduced using two-way coupling between the ocean and atmosphere and reduced further ~~still~~ by including feedbacks with surface waves. Lewis et al. (2018b) for example demonstrated this to be a general result, and is thought to result from the consistent simulation of the ocean and atmosphere and representation of feedbacks across the surface. SST results were improved relative to observations at a number of near-coastal sites during other times of the year (e.g. Figs. 3 and 4 of Lewis et al., 2018b), noting the impact of wave coupling to be more important during an autumn experiment period than found for the July period considered here. In general, while CPL_AOW results incorporating wave feedbacks were improved relative to CPL_AO, the main impact coupling in this study originates from inclusion of atmosphere-ocean interaction.

Although unavailable for the period considered here, the recent implementation of the AMM15 regional ocean configuration for operational forecasting across the NWS (Tonani et al., 2019, *this issue*) will provide a consistent ocean analysis for use in future studies in the region. This will substantially reduce the initial condition errors discussed in this study, and further work to examine the response to changing forcing with no initial condition bias is encouraged.

Given the sensitivity of ocean predictions to the surface forcing and coupling demonstrated here it is clear that more routine observations of the components of the surface energy and momentum budgets over the ocean would be of considerable value. In particular, co-location of complimentary measurements of the ocean and atmospheric boundary layers should better enable a more complete representation of surface feedbacks, in order to evaluate and improve prediction systems. Given these are challenging environments for making observations, making more use of the scarce sources of information currently available to the meteorological and oceanographic research communities should also be encouraged as a component of regional model development across both disciplines. The use of fully coupled prediction systems for research provides a framework in which to focus efforts on evaluating the interactions across the ocean surface, and to identify gaps in the current observational capability above and below the surface.

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Run ID	Model system[1]	Atm. coupled?	Wave coupled?	Information on meteorological forcing / coupling of ocean			
				Source	**Grid resolution**	**MetUM config.**	**Frequency**
FOR_GL	UKO3g	No	No	Global-scale MetUM NWP forecast	Approx. 17 km	GA6.1, GL6.1 (Walters et al., 2017)	Radiation: 180 min Winds: 60 min
FOR_HI	UKO3h	No	No	Regional uncoupled MetUM	Variable resolution, up to 1.5 km	RA1 (Bush et al., 2018)	All: 60 min
CPL_AO	UKC3ao	Yes	No	Regional coupled MetUM			
CPL_AOW	UKC3aow	Yes	Yes				

Table 1: Summary of ocean simulation experiments using forced mode and coupled systems. ([1] The model system names refer to model configurations documented by Lewis et al. (2018b).

	Full domain, 30 June – 30 July 2014			Celtic Sea region, 20 – 30 July 2014	
Experiment	**MD (K)**	**RMSD (K)**		**MD (K)**	**RMSD (K)**
FOR~~IX~~_GL	0.73	1.41		1.22	1.56
FOR~~IX~~_HI	0.40	1.27		0.63	1.17
CPL_AO	0.26	1.21		0.36	0.99
CPL_AOW	0.20	1.24		0.22	0.99

Table 2: Summary of mean difference of SST (Model – Observation) and root mean square difference (RMSD) comparing each simulation experiment with observations. Statistics computed using observations across the full AMM15 domain through July 2014 and those using only observations in the Celtic Sea region (Fig. 1(b)) during the last 10 days of July 2014 are listed.

	Net radiation, standard deviation (W m^{-2})				10 m wind speed, standard deviation (m s^{-1})		
Experiment	**Mean**	**Max**	**Min**		**Mean**	**Max**	**Min**
FOR~~IX~~_GL	55	190	10		1.33	1.88	0.82
FOR~~IX~~_HI	78	277	16		1.57	2.13	1.15
CPL_AO	81	268	17		1.56	2.23	1.08
CPL_AOW	79	274	15		1.54	2.14	1.11

Table 3: Summary of mean, maximum and minimum values of the spatial standard deviation of net radiation and 10 m wind speed computed across the Celtic Sea between 20 and 30 July 2014 for each experiment.

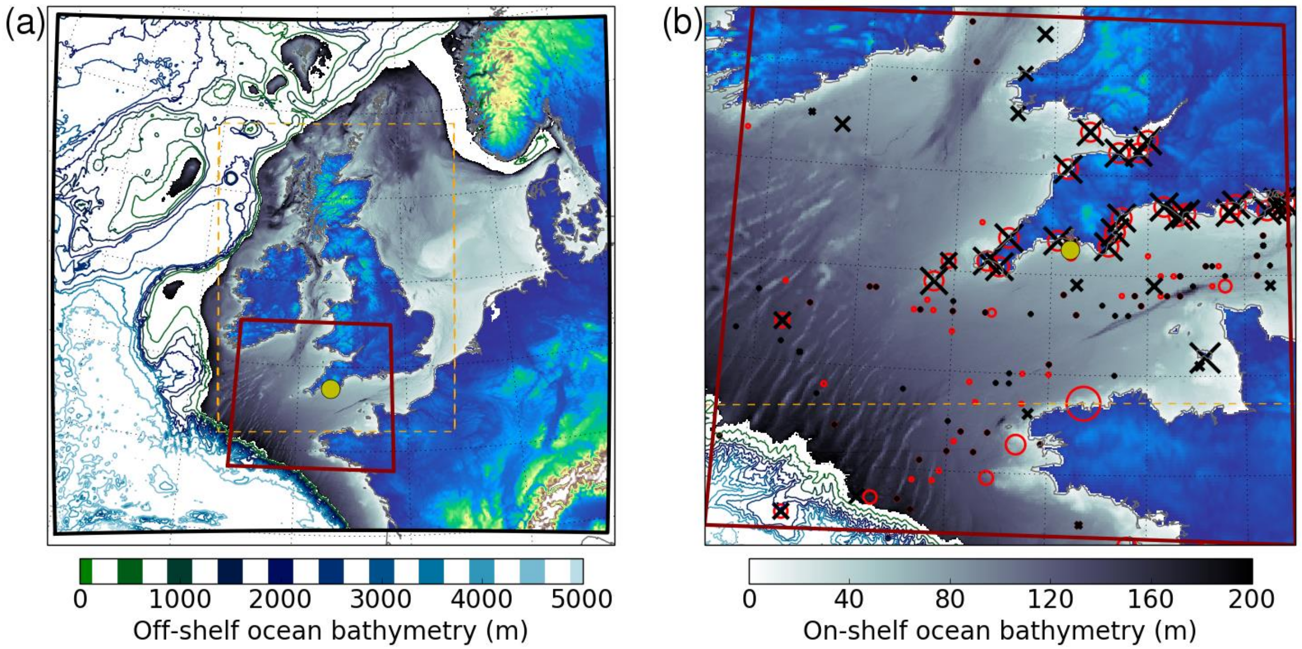

Figure 1: (a) Regional ocean model bathymetry for the NWS system. The colour scale is valid for locations off the shallow shelf region. Also shown are the Celtic Sea study area (red box) and location of the L4 ocean buoy (yellow circle). The dashed orange area marks the inner region of the ~~UKV~~ atmosphere model~~grid~~ where grid cells are regularly spaced, becoming stretched outside this region. (b) Zoom in of ocean model bathymetry across the red box region (note on-shelf colour scale) Also shown are potential locations of in-situ observations of wind (black cross) and SST (red circle) available for evaluation between~~on~~ 20 and 30 July 2014. The size of symbols illustrates the volume of data at each location. The L4 ocean buoy is also shown as a ~~(~~yellow circle~~)~~.

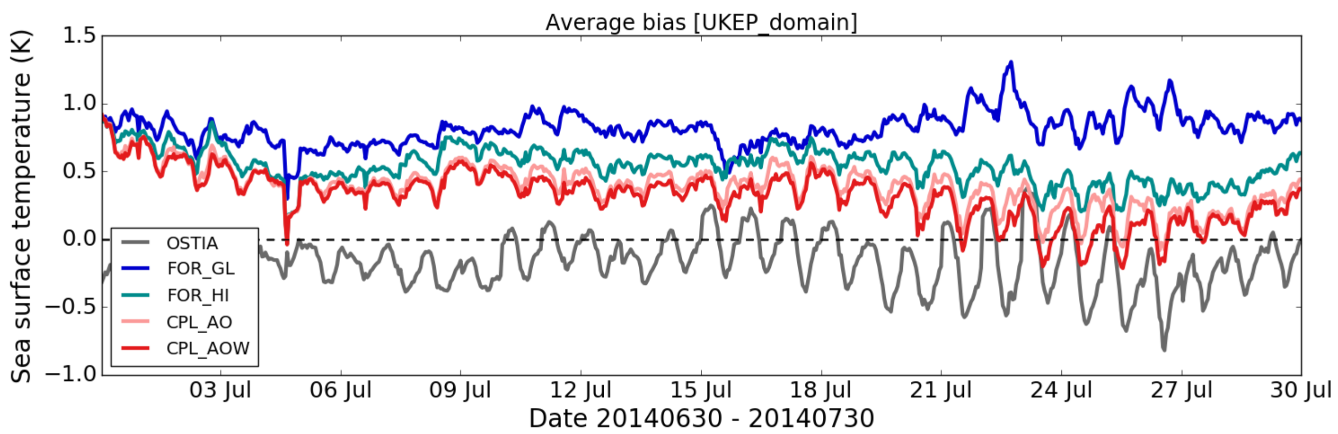

Figure 2: Evolution of mean bias (Model – Observation difference) in SST for each experiment during July 2014 relative to all in-situ observations across the AMM15 model domain. Also shown is a comparison between daily OSTIA SST and in-situ observations.

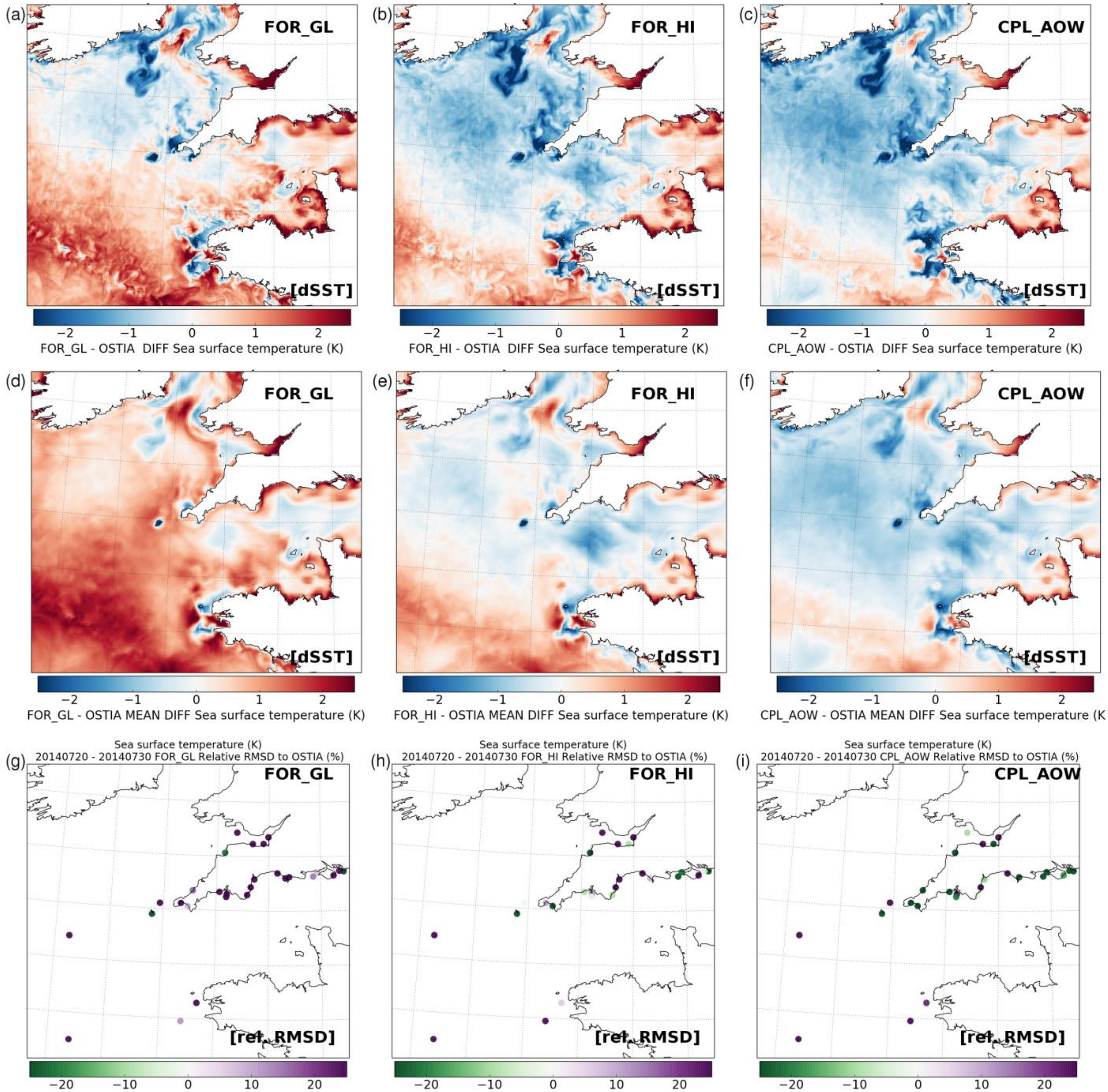

Figure 3: (a-c) Snapshot illustration of difference relative to OSTIA of the ocean model SST across Celtic Sea region valid at 1200 on 28 July 2014 from (a) FOR_GL configuration using global NWP forcing~~, and~~ (b) FOR_HI using 1.5 km resolution atmospheric forcing and (c) fully coupled CPL_AOW. ~~Shaded circles show the distribution of instantaneous observed SST.~~ (d-ee) Mean difference of SST for each configuration relative to OSTIA ~~impact of model coupling on SST~~ over 10 day period between 20 and 30 July 2014.~~, comparing CPL_AOW with FOR_HI.~~ (g-i) Percentage change in RMSD comparing SST results with in-situ observations for (g) FOR_GL, (h) FOR_HI and (i) CPL_AOW results relative to RMSD between OSTIA and in-situ observations over this period.

~~**Figure 4: Evolution of SST bias (model – observation) across Celtic Sea between 20 and 30 July 2014 for (a) FOR_GL and (b) CPL_AOW configurations relative to in-situ observations. The mean bias across all sites is shown as a thick line, bounded by +/- 1 standard deviation (darker shading) and maximum/minimum differences (lighter shading). (c) Percentage change in RMSD relative to in-situ observations for CPL_AOW results relative to FOR_GL over this period.**~~

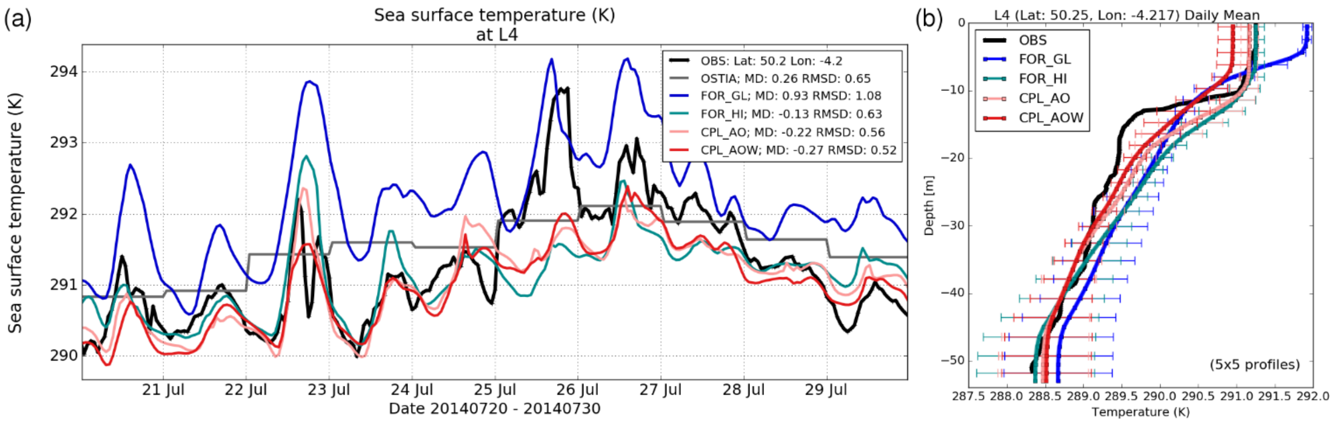

Figure ~~5~~4: (a) Time series of simulated and observed SST at the L4 ocean buoy (Fig. 1) between 20 and 30 July 2014. Model series are shown along with OSTIA as a mean from a 5 x 5 set of model grid cells nearest the observing site. (b) Vertical temperature profile observed by CDT at the L4 location on 28 July 2014 and daily mean profiles for each simulation experiment on that date. Error bars indicate 1 standard deviation around the spatial mean profile.

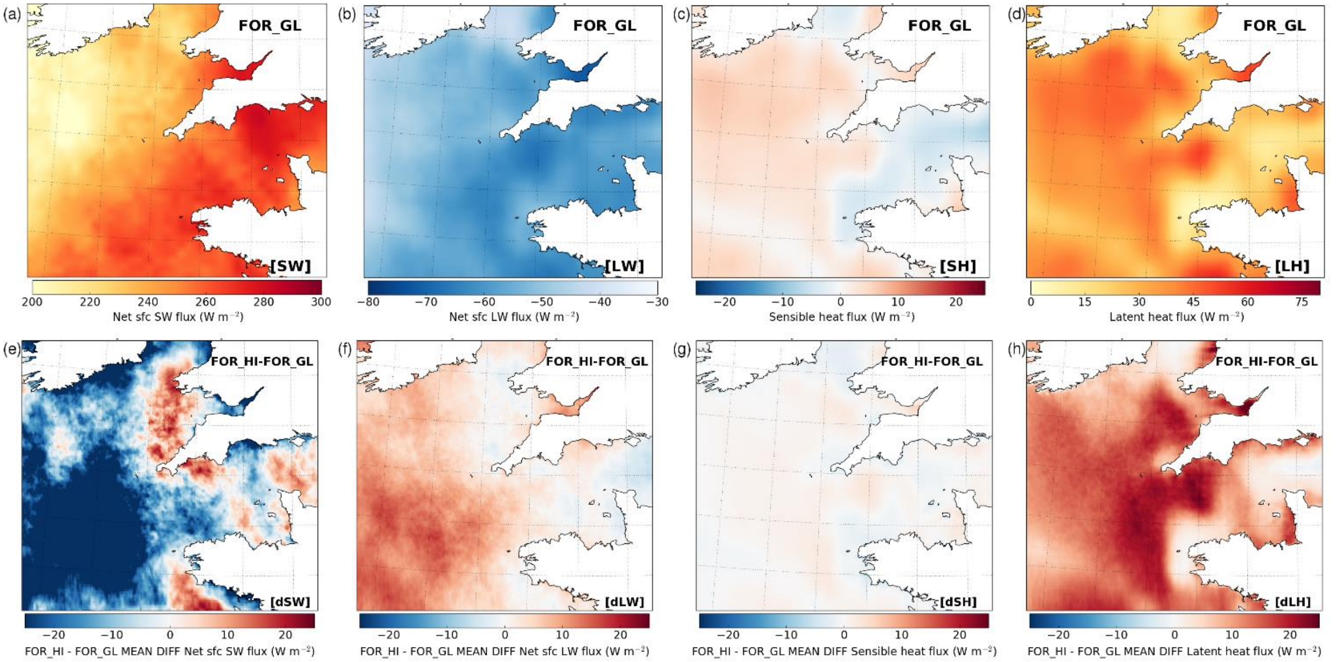

Figure 5: Illustration of surface energy balance terms as 10-day mean from FOR_GL forcing between 20 and 30 July 2014, of (a) net surface downwelling shortwave flux, (b) net surface downwelling longwave flux, (c) sensible heat flux and (d) latent heat flux. Differences between FOR_HI and FOR_GL 10-day means for each variable are shown in (e)-(h).

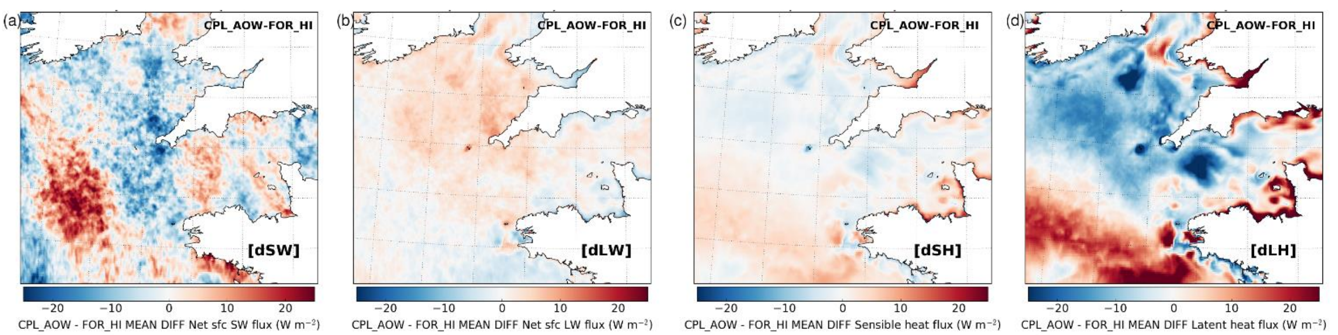

Figure 6: ~~Snapshot illustration of surface energy balance terms used in (a-d) FOR_GL and (e-h) FOR_HI atmospheric forcing, valid for 1200 on 28 July 2014.~~ The impact of model coupling across the Celtic Sea region ~~is~~ shown ~~in (i-l)~~ as the difference between 10-day mean~~averaged~~ CPL_AOW and FOR_HI results across all times of day for~~. Variables considered are~~ (a~~,e,i~~) net surface downwelling shortwave flux, (b~~,f,j~~) net surface downwelling longwave flux, (c~~,g,k~~) sensible heat flux and (d~~,h,l~~) latent heat flux.

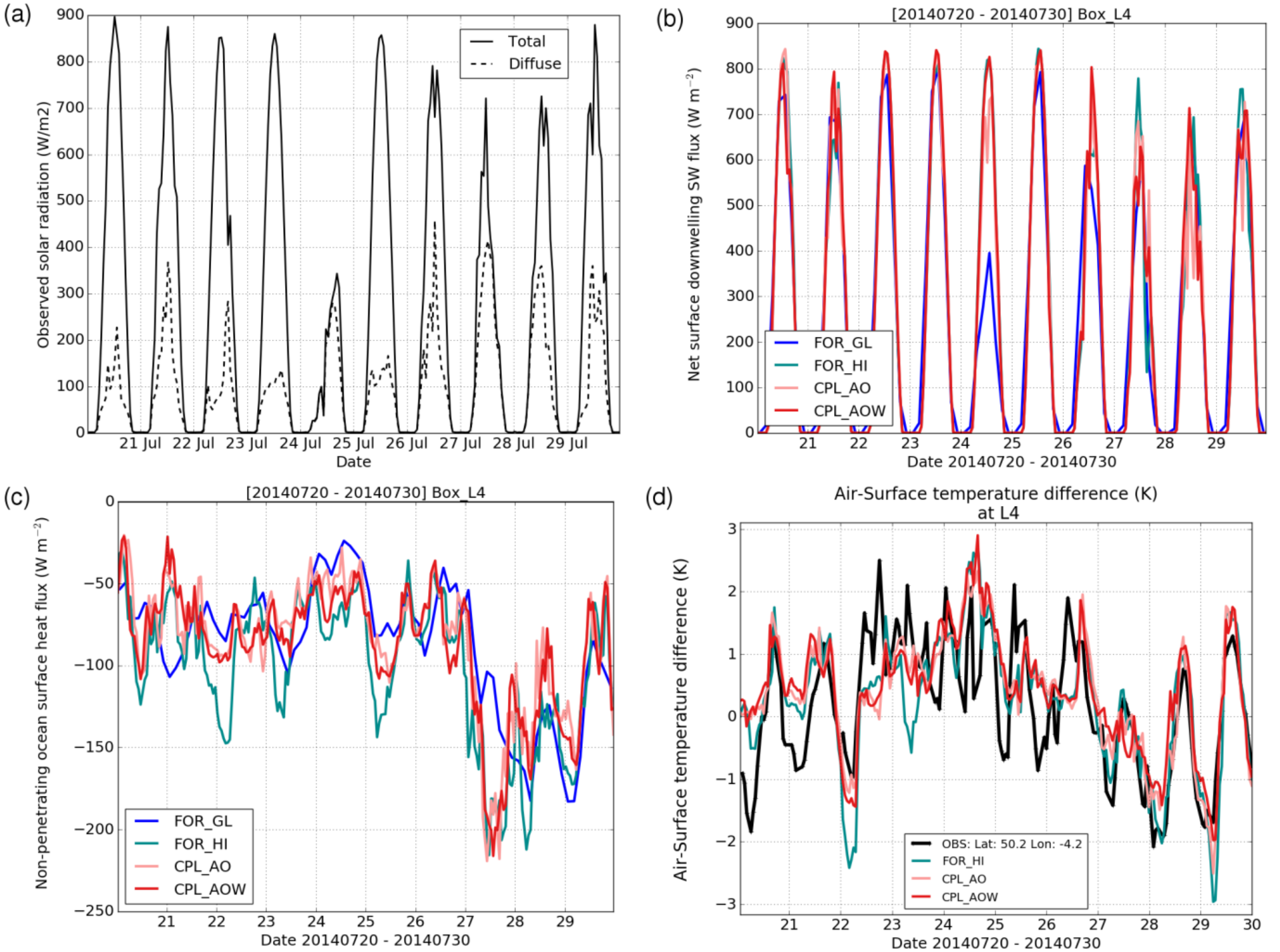

Figure 7: (a) Hourly mean observations of total and diffuse solar irradiance components at the L4 buoy between 20 and 30 July 2014. Time series of simulated (b) net surface downwelling shortwave flux, (c) non-penetrating ocean heat flux [Eq. 1] and (~~c~~) observations and simulations of near-surface temperature difference ($T_{air(1.5\ m)}$ – SST).

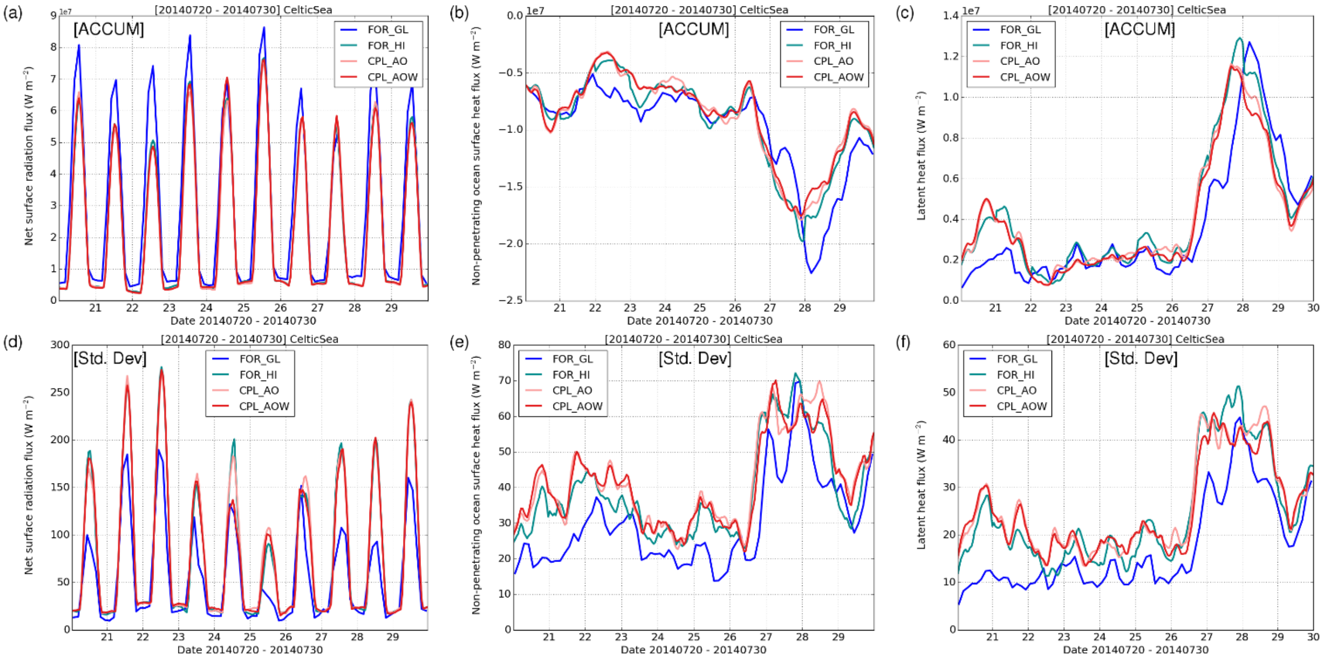

Figure 8: Time series of ~~mean~~ simulated surface energy balance variables across sea areas in the Celtic Sea region (Fig. 1(b)), showing~~for~~ accumulations of (a) net surface radiation [net short-wave + net long-wave], (b) non-penetrating ocean heat flux [Eq. (1)],~~ and~~ (c) latent heat flux, and time series of spatial standard deviations of (d) net surface radiation, (e) non-penetrating ocean heat flux and (f) latent heat flux across the region.

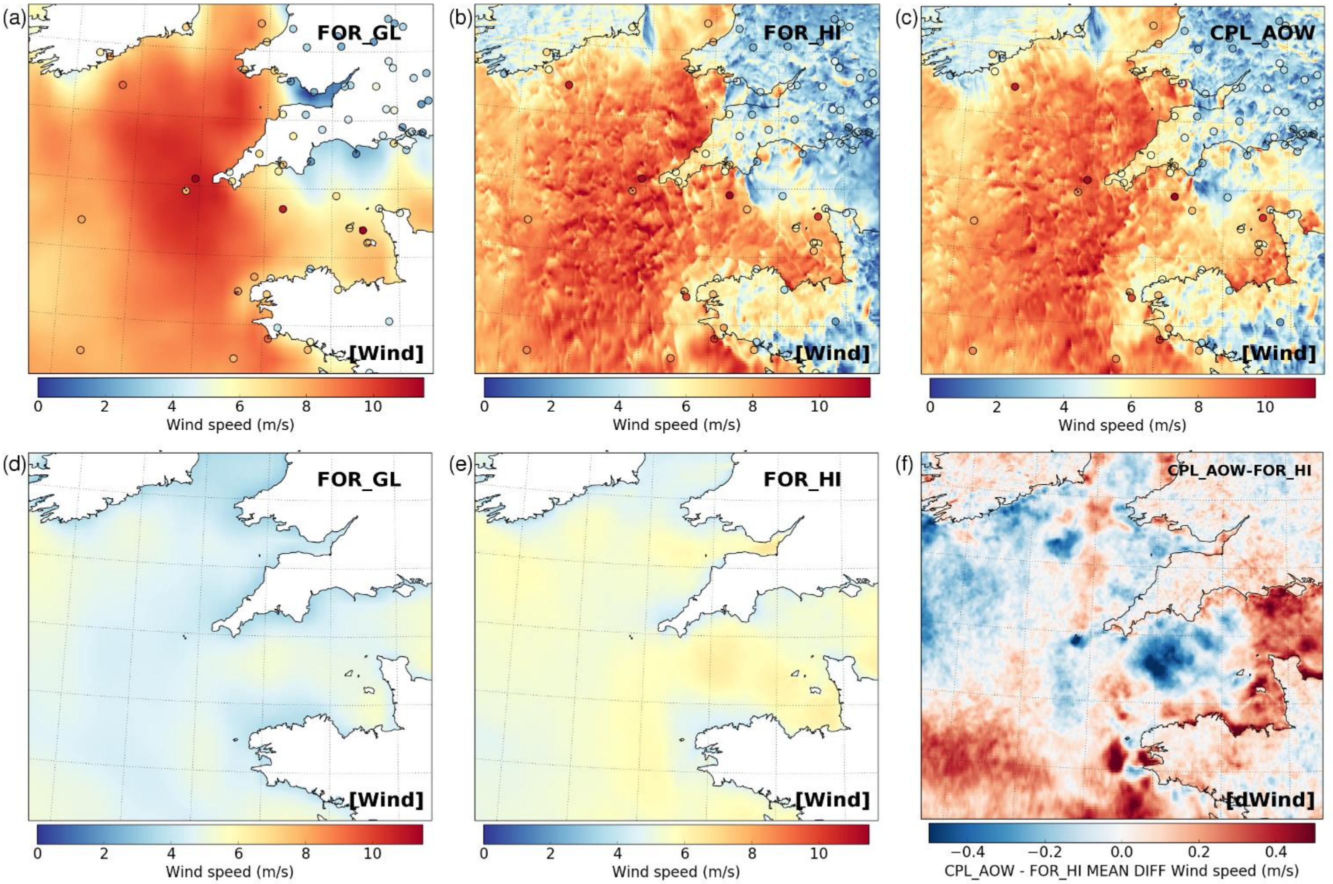

Figure 9: Snapshot illustration of near-surface wind speed forcing across Celtic Sea region valid at 1200 on 28 July 2014 used for (a) FOR_GL configuration (global-scale NWP), ~~and~~ (b) FOR_HI (1.5 km resolution atmosphere model) and (c) fully coupled CPL_AOW. Shaded circles show the distribution of instantaneous observed wind speed. (d~~e~~) Mean near-surface wind speed forcing of FOR_GL ~~impact of model coupling on near-surface wind speed~~ over 10 day period between 20 and 30 July 2014, (e) 10-day mean of FOR_HI wind forcing, and (f) difference between 10-day mean of~~comparing~~ CPL_AOW with FOR_HI.

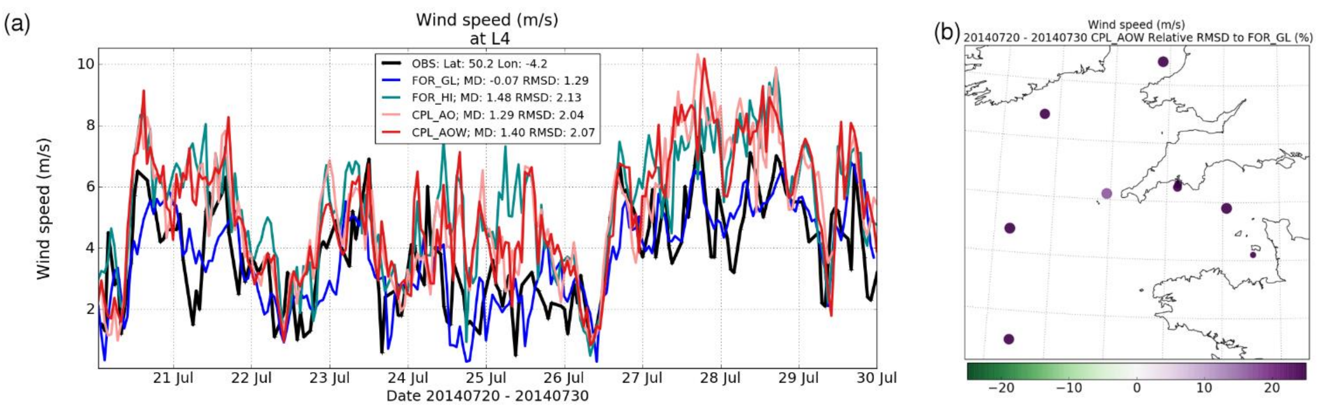

Figure 10: (a) Time series of simulated and observed near-surface wind speed at the L4 ocean buoy between 20 and 30 July 2014. Model series are shown as a mean from a 5 x 5 set of model grid cells nearest the observing site. (b) Percentage change in RMSD relative to in-situ observations for CPL_AOW wind speeds relative to FOR_GL forcing over this period.

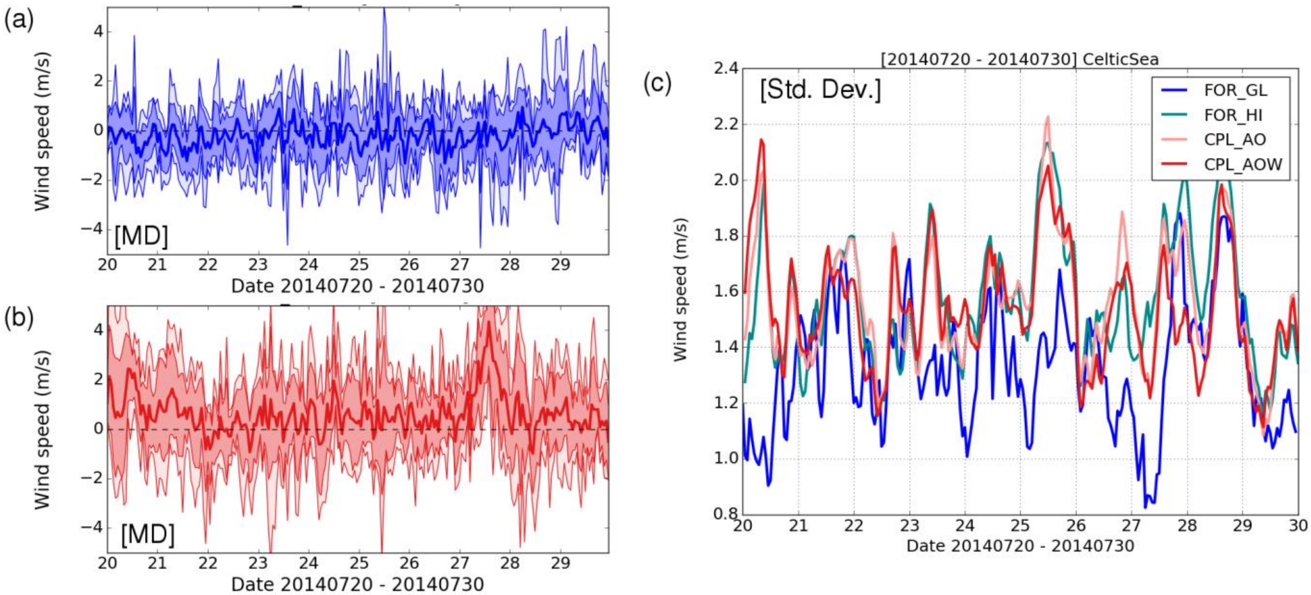

Figure 11: Evolution of near-surface wind speed bias (model – observation) across Celtic Sea between 20 and 30 July 2014 for (a) FOR_GL forcing and (b) CPL_AOW simulation relative to in-situ observations. The mean bias across all sites is shown as a thick line, bounded by +/- 1 standard deviation (darker shading) and maximum/minimum differences (lighter shading). (c) Time series of the spatial standard deviation of simulated wind speed across Celtic Sea for each configuration.

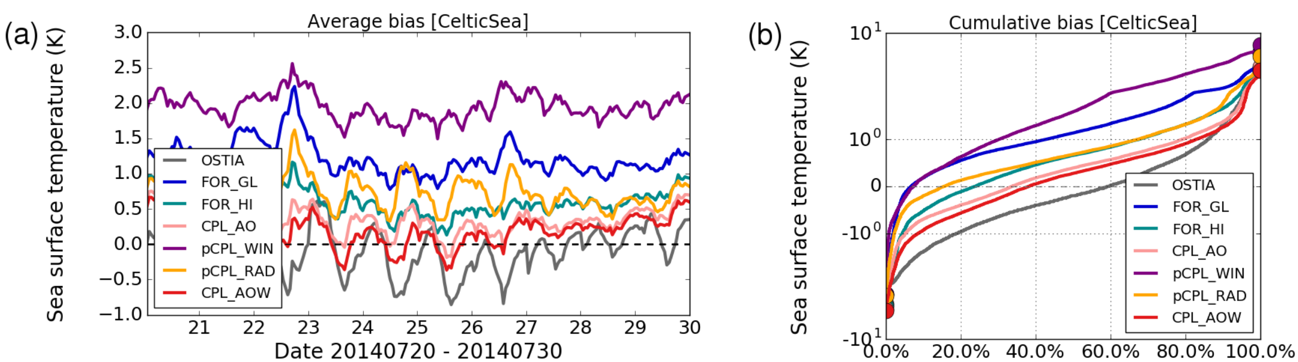

Figure 12: (a) Evolution of bias (model – observations) in SST for all ocean forced, coupled and partially coupled experiments together with OSTIA data between 20 and 3~~2~~0 July 2014 relative to all in-situ observations across the Celtic Sea study area (red box in Fig. 1). (b) Cumulative SST bias distribution for each experiment.