AMM15: A new high resolution NEMO configuration for operational simulation of the European North West Shelf

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Response to reviewers

General comments:

We would like to thank each of the reviewers for their time spent and comments provided. They showed a clear appreciation and understanding of the work presented, and have provided useful and constructive suggestions for improvement and/or further work. We provide responses to each reviewer below, with our responses to each comment shown in green. Line numbers stated in response refer to those in the marked-up document, which follows.

RC1: Anonymous Referee #1

The paper at hand, "AMM15: A new high resolution NEMO configuration for operational simulation of the European North West Shelf" describes in some detail the benefit from using an eddy-resolving model of the entire shelf, rather than just in limited, usually near-shore regions. The upgrade from the former system is not limited to a horizontal scale change, as everything except atmospheric forcing, vertical mixing and vertical resolution, has undergone a revision. A practical and very sensible choice.

The paper is excellently written. I think it would benefit from just a few points of clarification.

Comments.

p.5 line 5. Is the tidal forcing an open boundary condition or applied in the entire domain as a tidal potential? Not clear exactly how this is implemented. The paper says, "The amplitude and phase is provided for 12 tidal constituents (surface height and velocity)". Does NEMO convert this TPX input to forcing terms?

Tidal forcing is applied as both a tidal potential over the entire domain, as well as forcing at the open boundaries. The TPXO data is used specifically to provide amplitude and phase at the lateral boundaries. This has now been clarified in the text as follows:

P6 line 4: *Tidal potential is calculated across the domain for 12 constituents. In addition to this, tidal forcing is applied along the lateral boundaries. Forcing has been applied using the Topex Poseidon crossover solution (Egbert and Erofeeva, 2002), TPXO7.2, Atlantic Ocean 2011-ATLAS. For each of the 12 constituents, amplitude and phase (surface height and velocity) was obtained at a resolution of 1/12◦.*

p.5 line 20-27. Not entirely clear if the river data is applied as an annual climatology (one single average value per river) or daily climatology (the annual cycle included). I assume the reason for not using time series rather than climatology is that this was not available at the time.

The river data is applied as a daily climatology, so provides an annual cycle. This has now been rephrased to clarify:

River runoff is based predominantly on a daily climatology of gauge data, averaged over 1980-2014.

For AMM15, we believed this to be the best available product at the time. As stated in section 2.4, AMM7 had used timeseries from the E-HYPE hindcast data set. However, this data was believed to be the source of fresh water biases in areas such as the German Bight (O'Dea et al., 2017), so we chose not to use this data in AMM15. There were no other domain-wide timeseries available at the time. However, alternative data sets are being investigated for operational implementation, which would allow for interannual variability in runoff (see further comment below).

p.5 line 28. Please state the horizontal resolution of the atmospheric forcing. Only time resolution is given.

Done.

Atmospheric forcing is taken from … ERA-Interim (Dee et al., 2011). This has a spectral resolution of T255 (~79 km).

p.6 line 14. Are you stating that the use of river climatology based on gauge data is to be prefered over runoff time series based on a hydrological model?

As stated above, we decided that a runoff climatology was to be preferred over the E-HYPE data set that we had used previously. We would ideally want to include interannual variability in a hindcast simulation, and other solutions are being investigated for future use. However, we did not have access to a suitable alternative at the time.

To clarify that this choice related to a specific E-HYPE data set (version2.1) rather than hydrological models in general, we have specified the version number of the data set that was used:

… in AMM7 the rivers were based upon the European version of the hydrological model HYdrological Predictions for the Environment (E-HYPE, version 2.1) (Donnelly et al., 2015). … fresh water biases in areas such as the German Bight in AMM7 have been attributed to large riverine flux from this data set (O'Dea et al., 2017). This forcing data was then not chosen for AMM15.

p.12 line 1 and p.18 line 22. The (increased) fresh water bias in the Norwegian Trench is probably rightly connected with the Baltic boundary, which in AMM15 lies south of the Belt Sea. Is there any indication of the correctness of the modelled transport thru the Danish Straits? A large error could exist, possibly stemming from the not very realistic (in this region) 10m minimum depth. How does the model Belt Sea cross-section area, net water transport out of the Baltic, and fresh water export, compare with reality? It is also possible that the boundary data (from Gräwe et al.) is too fresh. This is one instance where the AMM15 high resolution model in some respects is described as leading to worse results than the previous 7km model. It could well be examined just a bit further, not necessarily by further experiments, as stated in the Conclusion. But using the data at hand. But that is just a suggestion.

We feel that the representation of the Baltic boundary is worthy of further study, which is outside the scope of this paper. However, we appreciate the reviewer's suggestion, and given their comments, we have provided further comment on the differences between the two models in the Baltic:

P11, L28: *The anomalies in this region are at times larger than those in AMM7, however there have been significant changes to the Baltic boundary conditions between the two models. Aside from the change in location, AMM15 also has the addition of SSH and barotropic currents forcing at the boundary (where there was none in AMM7). Therefore, we may expect significant changes in transport through the region, which would affect the Norwegian Trench heat and salt transport.*

P17, L32: *Given that both the Atlantic and Baltic boundaries have been altered in this configuration, the impact of such changes on the Norwegian Trench transport should be the subject of further study. While the addition of barotropic forcing at the Baltic boundary should lead to improvements in AMM15, 1.5 km resolution is still* *relatively coarse when compared to narrow channels within the Danish Straits. It is also possible that the difference in SSH forcing used at the Atlantic and Baltic boundaries could lead to an inaccurate flow through the region [e.g. Mattsson, 1996]. Further work is needed to assess whether the anomalies seen in AMM15 result from limitations in the model grid and bathymetry, or forcing at either the Baltic or Atlantic boundaries.*

p.12 line 8. How large is the fresh water reduction, in %?

The percentage difference is now stated in Section 2.4 as follows:

P7, L7: *… fresh water biases in areas such as the German Bight in AMM7 have been attributed to large riverine flux from E-HYPE [O'Dea et al., 2017]. The mean total freshwater input from E-HYPE v2.1 was found to be ~18% larger than the climatology. This forcing data was then not chosen for AMM15.*

p. 13 Fig. 5. Some of the graphics is white and thus invisible.

We have modified the colour scale to avoid the use of any white points, and improve the clarity here.

Typos:

p.4 line 14. Kattergat -> Kattegat

Done

p.16 line 6. uses of a -> uses a

Done

RC2: Anonymous Referee #2

General comments:

The paper "AMM15: A new high resolution NEMO configuration for operational simulation of the European North West Shelf" describes the upgrade of the current operational NEMO setup AMM7 run at the UK Met Office. In addition to the higher horizontal resolution of 1.5 km compared to 7 km in AMM7 there are also changes in bathymetry, model domain and boundary conditions. A good description of all major changes is given and results from the old and the new setup are compared to some extent. The paper is very well structured and written! It is, however, missing some aspects and would benefit from addressing some central questions.

An analysis of ocean current, transport and eddy kinetic energy is missing. At least a subchapter on current should be added to complete the paper.

We feel that analysis of currents and eddy kinetic energy (EKE) across is the domain is worthy of further investigation, and would be appropriate for a separate study rather than subsection here. We expect there to be larger differences seen within the small scale currents, and therefore more in depth comparison with observational campaigns is the subject of on-going work. Given that this study focuses on comparison of climatology on a domain-wide scale, we feel that such analysis is outside the scope of this paper. However, given the reviewers comment we have added comparison with tidal current meters, which will dominate the large scale circulation across the shelf (see below).

Central questions:

What is the purpose of the model? (If it shall be used in operational ocean forecasting: What are the main applications? What kind of output is needed? At what level of quality?) Answering these questions would naturally contribute to answering the central question (Q1) to be answered for all models in operational use: Is it fit for purpose?

Another aspect that needs to be addressed is the downside of upgrading to higher resolution: higher computational demands, increase in needed storage capacity and transfer time and very important for an operational model: the increased effort to extract the needed information from an increasing amount of data on the customer side. A table which compares AMM7 and AMM15 regarding number of wet grid cells, CPU time and storage needed should be added. In addition to question Q1 above a 2nd question (Q2) should be addressed: Is the upgrade worth it? (What was the expectation when starting the upgrade process? Has it already been reached? What is left?)

Based on these comments, we have added additional information on the operational system, future developments, and resulting outputs of interest. While there are developments yet to be made, the model has already shown to be fit for purpose, with comparable if not improved performance across the region. This new system also provides greater potential for future improvements. Further information and comments have now been added to the paper as follows:

Introduction (P2, L12):

This configuration will typically be used to produce forecasts on time scales of hours to weeks. Surface products are made available on hourly to sub-hourly timescales (e.g. temperature, salinity, velocity and surface height), with full-depth products also available on hourly, daily and monthly timescales. The full operational system will include data analysis. This system may also then be used to produce decadal reanalysis products, similar to that produced for the existing operational domain [O'Dea et al., 2017].

Before the inclusion of data analysis, it is important to understand any underlying biases in the free-running model, along with potential model drift. Here we present a 30 year non-assimilative run …

Model Description (P3, L25):

Compared to AMM7, the number of wet cells has increased by a factor of ~15. While the operational run time is still uncertain (pending future developments), the physics only AMM15 configuration takes approximately 400 node hours per day, compared to 20 node hours per day for AMM7. The storage costs have also increased (by a factor of ~11 for standard daily output files).

Boundaries (P5, L25):

For operational purposes, alternative boundary conditions will be used for both the Baltic and Atlantic boundaries. For the Atlantic, these will be derived initially from a 1/12deg configuration of the North Atlantic (NATL12). For the Baltic, boundary forcing will be provided from operational forecast products available through the Copernicus Marine Environmental Monitoring Service. However, neither of these data sets are available over a sufficient time period be used for this long hindcast.

…

The operational system will make use of the higher resolution ECMWF Numerical Weather Prediction model.

Discussion (P19, L27):

The increased resolution does make this model more expensive to run. However, the capacity is there to provide this new system, and with increased resolution there is greater potential for added value to end users. The full operational system will use different boundary conditions and include data assimilation. Therefore, it is not possible to say for certain how the skill of operational forecasts will compare with the existing system. However, this study provides insight into how the physics-only configuration performs, and where we should expect to see improvements compared to the existing 7 km domain. While some biases are common between the two models, there is an overall improvement in mean climate across the North West Shelf, and there is plenty of scope for further improvement.

…

With the increased resolution allowing for improved representation of mesoscale to submesoscale processes across the domain (such as eddies, fronts and internal tides), there is a wide scope for process studies here. The impact of such processes on forecast skill, will also be the subject of further study.

Specific comments:

CT1: Page 3, line 4: ... 'vertical cells can be masked ... ' How is this masking implemented? Percentage of cells masked?

This masking is determined based on the steepness of bathymetry. Model levels are smoothed to reduce pressure gradient errors, based on an envelope bathymetry. Any levels which are then deeper than the original bathymetry are masked. This is now clarified here in the text:

To reduce such errors, vertical cells can be masked over slopes which exceed a specified value, … . Terrain following coordinates are fitted to a smoothed envelope bathymetry, with the level of smoothing based on the chosen r_{max} value. In regions where the smoothed model levels become deeper than the input bathymetry, these levels are then masked. The r_{max} value was here chosen to be 0.1. …

CT2: Page 4, lines 3-5: Looking at Figure 1 it seems to be more natural to include the Bay of Biscay completely. Why was the southern open boundary chosen parallel to the Spanish coast?

The choice of boundary locations is already discussed on these lines, and earlier in Section 2.2. To include the whole Bay of Biscay, we would want to have the southern boundary further South along the Spanish coast, similar to the location used in AMM7. However, AMM15 has also been designed for use in coupled simulations, as stated on P4, lines 1-3. The existing domain was chosen with consideration of the Alps in relation to the location of the atmospheric boundaries. Having a southern boundary at the location used in AMM7 would also have led to an atmospheric component which covered a portion of the Mediterranean (which is masked in AMM7). So aside from the smaller computational costs, there were practical scientific justifications for the choice of boundaries.

To clarify this reasoning the text has been modified as follows:

… domain boundaries were chosen carefully, to ensure that they would not limit representation of major current pathways, whilst also ensuring that the grid would be compatible with coupled simulations (e.g. considering location of mountain ranges and the Mediterranean within the domain used for ocean-atmosphere coupling) (Lewis et al., 2017). This chosen common domain is now also in use at the Met Office for uncoupled operational UK weather forecasts (extending the existing UKV, e.g. Tang et al., 2013)

CT3: Page 4, lines 7-10: This seems to be an argument to include the overflow regions in the high resolution model setup to overcome the problems of simulating overflows in coarse models.

While we would expect to see improvement in the overflows with increased resolution across the Iceland-Faroe ridge, to accurately represent this region, the domain would have to be extended significantly further north, leading to a large increase in computational resource required (even without the consideration of coupling). In Section 3.2, we also discuss the fact that AMM7 has a cold, fresh bias introduced at the north-western boundary, along the Iceland coast. Having the domain south of Iceland then reduces the risk of such biases being introduced to the domain.

CT4: Page 4, lines 11-14: To move the boundary inside the Baltic Sea has some implications: If boundary conditions from another model shall be used (in this case from Gräwe et al., 2015) it must be ensured that both models show an equal resistance of the Danish Straits (meaning the same water level gradient across the Straits leads to the same volume and salt (!) transport, see, e.g., Mattson, 1996 a,b). Comparing the horizontal and vertical (!) resolution and the bathymetry of Gräwe et al., 2015 and the AMM15 setup and further looking at the results presented later on, this is obviously not fulfilled and should be addressed in future studies.

We agree that further studies should focus on the impact of changes to the Baltic boundary, and whether the transport through the Danish Straits is truly resolved. We do not have access to the full model configuration presented in Gräwe et al., 2015, so are unfortunately not able to carry out the suggested comparison here at this stage.

For the operational set up, alternative boundary conditions will be used (now stated in Section 2.3), and therefore further investigated. We appreciate the reviewer's comments here, and will certainly take them into consideration during this process.

While further analysis is outside the scope of this paper, given these comments, we have expanded the discussion within the paper as follows:

P11, L28: *The anomalies in this region are at times larger than those in AMM7, however there have been significant changes to the Baltic boundary conditions between the two models. Aside from the change in location, AMM15 also has the addition of SSH and barotropic currents forcing at the boundary (where there* *was none in AMM7). Therefore, we may expect significant changes in transport through the region, which would affect the Norwegian Trench heat and salt transport.*

P17, L32: *Given that both the Atlantic and Baltic boundaries have been altered in this configuration, the impact of such changes on the Norwegian Trench transport should be the subject of further study. While the addition of barotropic forcing at the Baltic boundary should lead to improvements in AMM15, 1.5 km resolution is still relatively coarse when compared to narrow channels within the Danish Straits. It is also possible that the difference in SSH forcing used at the Atlantic and Baltic boundaries could lead to an inaccurate flow through the region [e.g. Mattsson, 1996]. Further work is needed to assess whether the anomalies seen in AMM15 result from limitations in the model grid and bathymetry, or forcing at either the Baltic or Atlantic boundaries.*

CT5: Page 4, lines 26-28: Not to include wetting and drying and to specify a minimum depth of 10 m seems to be contradictory to the high horizontal resolution and can, depending on the purpose of the model, present a severe drawback. Major improvements when going to a much higher horizontal resolution are expected due to the better representation of bathymetry and coastline. The model region has a substantial portion of shallow coasts including large tidal mud flats. A minimum depth of 10 m at a horizontal resolution of 1.5 km seems to be inappropriate in this case. It is intended by the authors to be improved in future versions of the model and should be in the focus.

Wetting and drying is not currently available within NEMO vn3.6, but is in development for vn4.0. With no wetting and drying, a minimum depth has to be imposed on the bathymetry, to account for the large tidal amplitudes which may occur across the domain. We agree that the minimum depth imposed is a substantial limitation, and have already discussed the potential impact on tides on pages 8-9. However, we have also added further emphasis on this, with the following added to the discussion.

… it is then reassuring to see that AMM15 continues to provide a reasonable representation of the major tidal constituents. The minimum depth within the model remains a limiting factor here, so future improvements will focus on the addition of wetting and drying within the domain, which is currently in development for NEMO vn4.0.

We have also clarified that this choice is down to the fact that wetting and drying is not available. The following is stated in Section 2.2:

… minimum depth is specified as 10 m. While the tidal range may be smaller in other regions, this domain-wide minimum depth was chosen for simplicity, as well as consistency with previous configurations. Wetting and drying is not available within NEMO vn3.6, however it is currently under development for NEMO vn4.0. This capability will then be a priority for future development of AMM15.

CT6: Page 4-5: Chapter 2.3 is called 'Forcing and Initialization' but information on initialization is missing and should be provided for temperature and salinity at least. Was it the same for AMM7 and AMM15? (Figure 8 b, d hints to differences in initialization.)

Both models were initialised with conditions from ORCA025 simulations, which are the same as the respective forcing products for the two models at the time of initialisation. This differs for the two configurations. We have now clarified this in Sections 2.3 and 2.4 as follows:

P5, L17: For 1985-1989, … . This same simulation provided the initial temperature and salinity conditions for the AMM15 hindcast, with the model initialised from rest on 1st January 1985.

P6, L26: The simulations used to initialise and force AMM7 differ to those used for AMM15. As with AMM15, the period prior to 1990 has been forced with a free-running simulation, which also provided the initial conditions for 1981. However, the period of GLOSEA …

CT7: Page 5, lines 13-16: See CT4, the ratio of SSH difference across the straits and the volume transport should be checked.

As mentioned in response to CT4, we unfortunately do not have access to the full Gräwe et al. 2015 configuration. We agree that further studies should focus on the impact of changes to the Baltic boundary, and whether the transport through the Danish Straits is truly resolved. We appreciate the reviewer's comments and will certainly take these into consideration during future model developments.

CT8: Page 6, lines 24-26: The RMSE for amplitude in Table 1 shows an increase from AMM7 to AMM15 in all constituents but O1. Having the much higher resolution in AMM15 (and therefore much higher computational load) and that a new bathymetry was introduced (which is a major effort, when setting up a new model) in mind, a substantial improvement in reproducing tides should be expected; coming back to question Q2 (Is it worth it?). Especially the large increase in RMSE for M4 points to a severe problem, as M4 is much more influenced by the internal dynamics of the model as by the boundary conditions compared to all other constituents. Is seems that some further adjustment of the bathymetry and/or boundary conditions is needed. (Some one year model runs where a fraction of the M2 tidal amplitude is added/subtracted from the bathymetry might be a starting point.) And comment CT5 has to be mentioned again: Probably the mismatch of horizontal resolution and handling of shallow water strikes harder in the AMM15 setup than it did in the coarser AMM7. To introduce drying and flooding in the model and get rid of the minimum depth should come with a major improvement of tides along the coast.

As we mention in the paper, significant effort has been put into AMM7 over the years, to adjust parameters as well as the LSM to produce the best possible tides within the model. This time has not been spent with AMM15, since as the reviewer suggests, future development should initially look towards developing wetting and drying. Given this future development, we wanted to ensure that the neither the bathymetry or land-sea mask was overly modified from the original interpolation at this stage.

Given the fact that no tuning has been carried out, we feel encouraged that the majority of constituents show errors of a comparable magnitude. However, we agree that the minimum depth is a major limitation, and have now placed further emphasis on this within the text (as mentioned in response to CT5 above).

CT9: Page 9, line 10 & Page 10, line 28: The simulation of SST in an uncoupled model run is strongly dependent on the SST used as lower boundary condition in the atmospheric forcing, i.e. ERA-interim. Depending on the connection between the OSTIA SST product and the SST from the ERA-Interim product it might be helpful to introduce a 3rd row in Figure 3 showing the differences of ERA-Interim and OSTIA SST. It seems sensible not to expect smaller differences in the model than in the forcing data set (at least not on larger scales).

We do not currently have the ERA-Interim SST, so are unable to confirm the difference between that and OSTIA. However, we appreciate the reviewer's suggestion that this will be a limiting factor on the simulated SST error. Rather than adding the suggested third row to Figure 3, we have instead chosen to add a comment to the discussion here, to acknowledge that both OSTIA and ERA-Int SST will have a margin of error, which is likely to affect the biases shown here:

P12, L1: *… used to force both simulations. If the assumed SST in ERA-Interim differs to that of OSTIA, then this will be a limiting factor in the ability of the model hindcast to reproduce the observed SST.*

CT10: Page 10, line 21-24: See C4

As above, we appreciate that this warrants further investigation. While further analysis is outside the scope of this paper, we have expanded on this discussion to further acknowledge the differences between the two models (as detailed above).

CT11: Page 17, Figure 8 For the salinity in Figure 8 (b), (d) it seems that the AMM7 model is converging towards the AMM15 solution. Did both models start from the same initialization? If not, what are the differences?

Both models were initialised with their respective boundary forcing, from ORCA025 free simulations. This has now been stated in Section 2.4 (see CT6). For AMM7, the model was initialised with in 1981. For AMM15, the model was initialised in 1985. There may well be differences in the two data sets used here then. The reviewer is correct that both initialisation and boundary forcing will likely place a part in this trend, so this has now been stated here:

It is unclear what may cause the freshening seen in AMM7. However, this may be related to the different boundary conditions and initialisation. Both models are initialised and forced with free-running simulations prior to 1990. As AMM7 appears to drift towards the AMM15 mean value, this suggests there may be a larger difference between consecutive forcing sets for AMM7. The trend here may then be an adjustment of towards the state of the GLOSEA ocean.

CT12: Page 18, lines: 7-9 This should be concretized in the light of question Q1 and Q2. Is the improvement at the present stage sufficient to put the AMM15 into operation (having the much higher costs in mind)?

While this model is more expensive, improvements have already been seen and it has greater potential to provide an improved service through the coming years. This is now stated in the discussion (see response to Q1,2).

CT13: Page 18, lines: 9-11 This leads to the question: Why has, e.g., the vertical resolution not been improved from AMM7 to AMM15? This is easily done compared to changes in the horizontal resolution and doesn't lead to the same increase in the need for computational resources.

In shallow regions across the shelf, the vertical resolution will already be relatively high, with 50 vertical levels over depths ~10-50 m, the vertical resolution will be <=1 m (much less within surface layers using the stretched coordinate system). Therefore, it is felt that improvements in vertical mixing parameterisations or light attenuation schemes are likely to give a greater impact here. Increasing the vertical resolution further may also lead to stability issues in regions were the depth approaches 10 m.

CT14: Page 18, line 20: The assessment of transport is for sure an important issue. Before looking into this integrated quantity it would be advisable to look into the current. It can be expected that the step change in horizontal resolution from AMM7 to AMM15 has the largest impact on ocean current (and not on temperature and salinity). Despite the fact that there is a lack of observations for a proper validation on regional scale, it is therefore suggested to add a subchapter on currents. A comparison of mean surface and vertical integrated currents from AMM7 and AMM15 would already be a substantial contribution to the completeness of the paper. To add an estimate of eddy kinetic energy from both models would be perfect.

We feel that analysis of currents and EKE across is the domain is worthy of further investigation, and would be appropriate for a separate study. We expect there to be large differences seen within the small scale currents, and therefore more in depth comparison with targeted observations is the subject of on-going work. Given that this study focuses on comparison with climatology on a domain-wide scale, we feel that such analysis is outside the scope of this paper. However, in light of the reviewers' comments we have added analysis of tidal currents, which make a significant contribution to circulation across the shelf. The summary statistics from this analysis is now shown in Table 1, and reference to these results has been added in Section 3.1:

P7, L24: *A summary of errors in the semi-major axis of tidal currents is also presented in Table 1. This analysis follows the same method used in Guihou et al. [2017]. Again, the RMSE and bias are found to be of a similar magnitude in the two configurations, but with a slight increase in both M2 and M4.*

A note on the need for further studies has also been added to the Discussion:

P20, L21: *Further work is also needed to assess currents and transport within the region, along with their impact on model hydrography.*

L33: *With the increased resolution allowing for improved representation of mesoscale to submesoscale processes across the domain (such as eddies, fronts and internal tides), there is a wide scope for process studies here.*

References:

Mattsson, J. (1996a), Analysis of the exchange of salt between the Baltic and the Kattegat through the Öresund using a three-layer model, J. Geophys. Res., 101(C7), 16,571–16,584.

Mattsson, J. (1996b), Some comments on the barotropic flow through the Danish straits and the division of the flow between the Belt Sea and the Öresund, Tellus, Ser. A, 48, 456–464.

RC3: Anonymous Referee #3

This paper describes the development of the new UK operational forecast model for North West European shelf seas (AMM15). This model will be replacing the current operational model (AMM7). The predominate change is the horizontal grid resolution, increasing to 1.5 km from 7 km, enabling finer scale processes (such as mesoscale eddies) to be resolved. The paper is very well written but could benefit from some clarifications (listed below). I did struggle with a number of the figures when using a print out. Going back to the PDF and zooming in was helpful and enabled the grey to be distinguished from the white background. Whist this isn't critical – i.e. it's an online journal – some thought could be given to making the figures clearer.

We have now modified the colour scale in Figure 5, to avoid the use of any white points, and improve the clarity here.

The model is described as being the next generation ocean forecast model. Some introduction as to what this means exactly would be useful, e.g., is the model run weekly/daily and how long a forecast is simulated? The model must also be more computationally demanding that its predecessor, AMM7, and there must be computational considerations when operationalising it. Further to this, the paper describes a set of hind cast simulations. Would operationalizing the model involve using different forcing data? A short discussion on this would be interesting.

Following the reviewers' comments we have now added additional details regarding the operational implementation throughout the paper, including the target products, potential changes to model forcing, and rationale for the experiment designed used here.

Additions to the text are outlined below:

Introduction (P2, L12):

This configuration will typically be used to produce forecasts on time scales of hours to weeks. Surface products are made available on hourly to sub-hourly timescales (e.g. temperature, salinity, velocity and surface height), with full-depth products also available on hourly, daily and monthly timescales. The full operational system will include data analysis. This system may also then be used to produce decadal reanalysis products, similar to that produced for the existing operational domain [O'Dea et al., 2017].

Before the inclusion of data analysis, it is important to understand any underlying biases in the free-running model, along with potential model drift. Here we present a 30 year non-assimilative run …

Model Description (P3, L25):

Compared to AMM7, the number of wet cells has increased by a factor of ~15. While the operational run time is still uncertain (pending future developments), the physics only AMM15 configuration takes approximately 400 node hours per day, compared to 20 node hours per day for AMM7. The storage costs have also increased (by a factor of ~11 for standard daily output files).

Boundaries (P5, L25):

For operational purposes, alternative boundary conditions will be used for both the Baltic and Atlantic boundaries. For the Atlantic, these will be derived initially from a 1/12deg configuration of the North Atlantic (NATL12). For the Baltic, boundary forcing will be provided from operational forecast products available through the Copernicus Marine Environmental Monitoring Service. However, neither of these data sets are available over a sufficient time period be used for this long hindcast.

…

The operational system will make use of the higher resolution ECMWF Numerical Weather Prediction model.

Discussion (P19, L27):

The increased resolution does make this model more expensive to run. However, the capacity is there to provide this new system, and with increased resolution there is greater potential for added value to end users. The full operational system will use different boundary conditions and include data assimilation. Therefore, it is not possible to say for certain how the skill of operational forecasts will compare with the existing system. However, this study provides insight into how the physics-only configuration performs, and where we should expect to see improvements compared to the existing 7 km domain. While some biases are common between the two models, there is an overall improvement in mean climate across the North West Shelf, and there is plenty of scope for further improvement.

…

With the increased resolution allowing for improved representation of mesoscale to submesoscale processes across the domain (such as eddies, fronts and internal tides), there is a wide scope for process studies here. The impact of such processes on forecast skill, will also be the subject of further study.

P. 5 lines 20-26: I assume that a time series of freshwater flux/discharge was specified for each river? This could be made clearer. In addition, was river temperature and salinity time series used, or if not what values were used or assumptions made? Were daily/monthly averages used and/or what temporal resolution was used?

We have clarified our description of the riverine forcing. The climatology varies on a daily time scale for each river point. There was no data provided for temperature and salinity at the river mouth. Instead, the temperature is assumed to match the local SST and any volume flux is assumed to be a fresh water flux (salinity = 0). Text has been updated as follows:

River runoff is based predominantly on a daily climatology of gauge data, averaged over 1980-2014. … For each river point, a daily freshwater flux is specified with the depth dependent on the average ratio of runoff to tidal range (based on estuary classifications discussed Cameron and Pritchard (1963)). The runoff temperature is assumed to match the local SST, with no temperature data included in the climatology.

P. 6 line 24: RMSE is not defined.

Done: *route-mean-square error (RMSE)*

Figure 2: The co-tidal charts are quite hard to read, especially on paper/print out. The amplitude is OK, and having a discrete colour scale is helpful, but the phases (white to black) do not seem to equate to the colour scale (grey to white). It's also hard to see the black phase lines on the blue background. In the lower panels (c – f) There is a lot of overlapping observational data points which makes these hard to read. It's hard to know how exactly to make this clearer apart from making the figure larger. This figure could be split (a, b) and (c – f) allowing them all to be larger/clearer.

We have chosen to keep this as one figure, to ensure that the anomalies can be compared directly with the co-tidal plots. However, we have now modified this figure to update the contour colours and make the anomalies clearer.

P. 7: The text says that the amplitude of the M2 tide has reduced errors off the west coast of Scotland. Where exactly do you mean, i.e. out beyond the Outer Hebrides or at the coast (Mull of Kintyre)?

This has been clarified: *The amplitude of M2 also has reduced errors off the west coast of Scotland, particularly around the Kintyre Peninsula.*

P. 9 line 10: It would be helpful if how the SST anomalies were calculated was explained in the text.

This is now stated within the figure caption as follows:

Seasonal SST anomalies for model minus observations … All panels show 20 year-mean anomalies, for period 1991-2010, with anomalies calculated as $\overline{SST_{AMM}} - \overline{SST_{OSTIA}}$.

Figure 3 and supporting article text: DJF, MAM, JJA and SON should probably be defined (probably in the text as this is where these abbreviations are used and maybe simply as what season they are). Also, the text refers to season by name in many cases (e.g. P. 10 line 21) and whist everyone knows by spring you mean MAM, this should also be defined. This could all be done early on by saying seasonal means were calculated for winter (DJF), spring (MAM), and so on...

Seasons have now been defined as they are introduced within the text e.g.:

AMM7 has its largest mean SST anomalies in winter (DJF) and spring (MAM), with a cold bias dominating off-shelf. …

RC4: Anonymous Referee #4

Summary:

The paper presents results from an old and new setup of NEMO, covering the Northwest shelf region (NWS). It includes a model inter-comparison and validation against observations. The new model configuration will replace the previous setup in the operational model setup at the UK MetOffice. The paper focuses on results based on seasonal and yearly calculations. The results are well presented and it clearly illustrates that the new high resolution setup delivers better salinity and temperature results on seasonal to climatic time scales. Furthermore, tidal signal is also better described in the new setup. Model developments and validation are too rarely presented in journals, and it is very interesting to read model development at operational centers. The manuscript discusses processes near the shelf edge, which could be benefitted by the scientific community. Throughout the manuscript results from three regions are presented: 1) Outer shelf, shelf and Norwegian trench. It would be nice if the results were presented in this order for all sections. Sometimes the Norwegian section comes second and sometimes it comes last.

We appreciate the author's suggestion here, but the order was chosen based on the emphasis of results in each section. We feel that it would not be appropriate to restructure the entire text at this time, but will keep these comments in mind for future publications.

Central issues

The authors should present which operational products are produced based on results from the operational model. If products are related to storm surge events, search and rescue or other weather related issues, then this manuscript lacks validation on these phenomenons. It could be analyzing peak error on sea level or presenting results from a storm surge event.

For an operational model, the results on time scales from hours to weeks are also important, especially on sea level. Excluding sea level variations from the papers makes it impossible to know if the barotropic transports are sufficiently well simulated, especially if (as the author states) S/T-climate are mainly governed by vertical processes. Still, the (non-tidal) barotropic signal has effect on the state of the North Sea on both short and longer time scales.

Given this and other reviewers' comments, we have added further detail regarding the operational system into both the introduction, model description and discussion within the article.

The AMM15 domain will initially be used to produce forecasts on scales of hours to weeks. In the future, the model may also be used to produce decadal reanalysis products for the region. However, the operational system will also make use of data analysis (with available surface satellite and in situ observations). Here we choose to focus on the long term climatology, to understand the ability of the model to represent the mean state, before the addition of data assimilation.

For surge forecasting, there is a separate NEMO-Surge configuration (purely barotropic model), which is currently under development [e.g. Furner et al., 2016; O'Neill et al., 2016]. The upgrade of this surge configuration from the AMM7 to AMM15 domain is yet to be completed.

Furner, R., Williams, J., Horsburgh, K., and Saulter, A. (2016), NEMO-surge: Setting up an accurate tidal model, Weather science technical report 610, Met Office.

O'Neill, C., Saulter, A., Williams, J., and Horsburgh, K. (2016), NEMO-surge: Application of atmospheric forcing and surge evaluation, Weather science technical report 619, Met Office.

One main conclusion presented in Section 4 is:

Abstract: "Since there has been no change to the vertical resolution or parameterization schemes, performance improvements are not expected in regions where stratification is dominated by vertical processes, rather than advection."

It seems like that this conclusion is based on pp13, line 2-6, thus rather short for being such a central parts in conclusions/abstract and I believe it deserves more attention in Section 3

Agreed. This has now been expanded in response to further comments below.

Minor comments

pp 4, line 28. Why is the minimum depth spec. to 10m? Would it not be better to set minimum depth to much less, maybe 3m, and locally increase the depth to at least 10m in Bristol Channel and Gulf of St. Malo? Consider to include a comment on this in the manuscript.

We did run some tests with a reduced minimum depth (6 m), however this did not lead to significant improvements across the domain. We therefore kept the minimum depth as 10 m to be consistent with that used in the previous configuration, and for simplicity across the domain. In future configurations, the priority will be to introduce Wetting and Drying, so this minimum depth is a temporary solution. Further comment has now been added in Section 2.2:

… minimum depth is specified as 10 m. While the tidal range may be smaller in other regions, this domain-wide minimum depth was chosen for simplicity, as well as consistency with previous configurations. Wetting and drying is not available within NEMO vn3.6, however it is currently under development for NEMO vn4.0. This capability will then be a priority for future development of AMM15.

pp5, line 18. Method for Tidal forcing is only valid for AMM15. Method for Tidal forcing for AMM7 is described on pp6 line 16. Merge these two sections into one, preferably at pp.5.

We prefer to keep the AMM7 description focused within Section 2.4, for ease of reference.

pp 6, line 22-23. There are shifts in the position of two amphidromes. Please comment if that is good or bad.

Both shifts coincide with reduced errors in amplitude and phase. This is now stated in the text:

At both these locations, this coincides with reduced errors in amplitude and phase in AMM15.

pp. 6, line 32. Add English to "Channel". Not all may come to think of English Channel when just writing Channel.

Done.

Caption to Figure 2 and Table 1. Refer to data source in text also (only in fig caption is not enough).

Now stated in text:

The mean bias and route-mean-square error (RMSE) of major constituents, compared with available tide gauge observations (British Oceanographic Data Centre), is presented in Table 1.

To my knowledge, non-British tide gauge data (e.g. Danish, Norwegian, and German) is not available at BODC.

The vast majority of data used here is available through BODC. However, the author is correct that some non-British sites may not be available here. The full data set was originally obtained from National Oceanography Centre Marine Data Products. This has now been clarified here.

Caption: *Observations are tide gauge data obtained from National Oceanography Centre (NOC) Marine Data Products and the British Oceanographic Data Centre (BODC).*

Figure 2. Label and add units to the vertical bars to the right of panels. I do not see the meaning of the phasebar. For example, it is not possible to differ between phase=80 and phase=240.

Labels have now been added, and the colour scale for phase contours modified, to increase clarity.

Comment to pp 8, line 6. Tidal signal downstream of shallow regions will also be affected by too deep minimum depths. Please comment on downstream consequences.

We agree, and have added the following comment in the subsequent paragraph:

P9, L10: *Therefore, impacts on tidal circulation are expected to be found downstream of any apparent depth anomalies, as well as more widely across the domain.*

pp9, line 12, Are OSTIA observations skin or bulk temperature? Are there any problems validating this observed temperature to a 10m thick model surface layer level? Please comment on that, especially for regions that have seasons with expected shallow surface layers. Maybe some regions do have thicker than 10m for all seasons, others not. I think addressing this will help the reader to interpret the validation better (also related to next three comments).

The OSTIA product used here is the bulk temperature (equivalent to ~20 cm). This is now stated in the text here:

… (Merchant et al., 2014). This analysis provides a 20 cm SST product, and is therefore useful for comparing to the uppermost SST in ocean models.

With the Siddorn and Furner (2009) stretching function, the model surface layer has a maximum thickness of 1 m (not 10 m). Across the shelf, the surface layer will be much shallower (there is no minimum set). Therefore, while the model may not fully resolve the skin temperature, the bulk should be reasonably well reproduced. We do appreciate that having a minimum bathymetric depth will lead to greater thermal inertia however, and this is acknowledged in the text (see comments below).

pp 10, line 28-31. Thermal inertia in model during summer that causes a delay in summer heating, and a delay in cooling during early fall (when warm surface layer is being developed and maintained) is , to at least some extent, explained by a too thick surface layer (=10m).

The surface layer is not 10 m thick (there is a maximum of 1m, likely much thinner over the shelf). However, we appreciate that in fully-mixed areas, the minimum depth of 10m is going to contribute to thermal inertia, in addition to any difference in stratification. This is now stated in the text:

P12, L5: *This may then be related to weak stratification across the shelf. In shallow coastal regions (which are already fully-mixed), the 10 m minimum depth could also be a contributing factor.*

pp10, line 25-35. Hypothesis that too warm SST during spring due to too shallow mixed layer depth could be verified by producing a MAM and SON figure similar to Fig6a. Consider to include that analysis.

The hypothesis discussed here is that the stratification is too weak in the southern North Sea, allowing heat to build up within the deep ocean, leading to warmer SST in autumn. To demonstrate such differences in stratification, we choose to focus on JJA, since this is when stratification should be strongest across the region. This is also the season with the largest number of EN4 profiles, placing greater confidence on any resulting anomalies.

In the following paragraph, we go on to discuss over stratification in coastal regions, however there would be too few profiles in the EN4 data set to make a mean regional comparison along the coast, such as those shown in Figure 6. In this region, any difference in model and observed bathymetry would also have a greater impact on the results.

pp12, line 33. Too cold surface water may be explained by the 10 m thick surface layer. This could be investigated by computing the evolution of a single column model with different vertical resolutions, but with same forcing and initial conditions, but this is just a suggestion.

As above, the 10 m minimum depth will be a factor. We appreciate the reviewer's suggestion, and agree that analysis with a 1D model could be a potential avenue for further research. Vertical mixing schemes on the shelf are certainly a focus for future improvement, and we will take this suggestion into consideration.

Fig. 8 and text pp. 17, line: 5-15: These two paragraphs do not add much information to the study; more than that AMM7 has larger interannual variability. But it cannot be verified which one of these setups does the best job. The observations referred to, cover twice the simulation period and are presented rather vaguely with only sign of trend (positive) but no rate of change or mean value for the period. If there is a trend, then stability in AMM15 is not reassuring. It should drift. Furthermore, if AMM15 simulates the long term mean value rather good, the decrease in AMM17 until early 2000s may be a good thing, and maybe the increase after 2003 could just as well agree very well with the observed long term trend. My conclusions based on your results may be considered rather speculative, but that is exactly my point. From the interannual salinity data presented in this paper, the authors' results are speculative. More results are needed, or the paragraph should be rewritten or deleted.

We feel that it is worth considering the variability of the simulations, as the configuration will also be used to produce reanalysis for the region in the future. It is therefore useful to understand the temporal variability (or stability) of the model before the addition of data analysis. This comment has now been added to the introduction:

P2, L10: *The next generation ocean forecast model for the European NWS is introduced here, … This configuration will be used to produced forecasts on daily to weekly timescales, as well as monthly-mean reanalysis for the region.*

We have also now restructured this paragraph taking both these comments and that of other reviewers into consideration:

P 19, L5-: *For salinity, there are no shelf-wide data sets for comparison … While we can't say for certain, the stability shown in AMM15 may then be reassuring, suggesting that the model is in a relatively stable state. It is unclear what may cause the freshening seen in AMM7. However, this may be related to the different boundary conditions and initialisation. Both models are initialised and forced with free-running simulations prior to 1990. As AMM7 appears to drift towards the AMM15 mean value, this suggests there may be a larger difference between consecutive forcing sets for AMM7. The trend here may then be an adjustment of towards the state of the GLOSEA ocean.*

Title of section 4 is "Discussion and Conclusions": I do not detect so many conclusions, more discussion and future work. It would be nice to highlight conclusions further in text or add some conclusions drawn from the paper; alternatively rename Section 4 to "Discussions and Future work".

In response to this as well as other comments, the section has been renamed as "Discussions and Future Work".

The only obvious conclusion to me is:

Section 4: pp 18, line 9-11 "Given the fact that climate on the shelf can be predominantly driven by a balance of vertical forces (surface buoyancy fluxes and vertical mixing) rather than horizontal advection, it is not surprising that the two models are similar. Both have the same atmospheric forcing, vertical mixing schemes and vertical resolution." This is very interesting and I think it should be more clearly presented in Section 3. Vertical processes may govern the salinity/temperature climate in the North Sea, but advection may very well a dominating factor during storm surge events.

This result had been stated in Sections 3.2 and 3.3, however given the comments here we have now placed greater emphasis on this in Section 3.3:

P17, L10: *Overall, while there have been some improvements in AMM15, similar biases remain in stratification across the shelf. Given that both models have the same number of vertical levels, vertical mixing schemes, and surface forcing, this result is not entirely surprising. Across large areas of the shelf, the climate will be predominantly driven by a balance of vertical forces (surface buoyancy fluxes and vertical mixing) rather than horizontal advection. It is therefore clear that further work is needed to improve the representation of these vertical processes. …*

Section 4: There are no conclusions and/or discussions from tidal section. In fact, it took me a while to realize that it is only baroclinic features are discussed. Please add a paragraph of the tidal-results presented in 3.1. It could be something like: Tidal signal within a model setup covering the North Sea is to a large extent determined by the boundary conditions and bathymetry. AMM15 and AMM7 have different bathymetry and tidal forcing at the open boundary. It seems like this step is larger than comparing two different models (e.g. NEMO and ROMS) with same bathymetry and tidal forcing (and advections schemes). To me, the tidal part is not considered to be an update (from AMM15 to AMM7), but a replacement to a new setup. Feel free to add something like this, or choosing some other angle of the tidal-results presented in Section 3.1.

We agree that this is worth mentioning, and have now added the following:

P20, L1:: *Tidal signal within a regional model configuration is to a large extent determined by the boundary conditions and bathymetry. AMM15 and AMM7 have both different bathymetry and tidal forcing at the open boundary. Given this significant change in configuration, it is then reassuring to see that AMM15 continues to provide a reasonable representation of the major tidal constituents. The minimum depth within the model remains a limiting factor here, so future improvements will focus on the addition of wetting and drying within the domain, which is currently in development for NEMO vn4.0.*

AMM15: A new high resolution NEMO configuration for operational simulation of the European North West Shelf

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Abstract. This paper describes the next generation ocean forecast model for the European North West Shelf, which will become the basis of operational forecasts in 2018. This new system will provide a step change in resolution, and therefore our ability to represent small scale processes. The new model has a resolution of 1.5 km, compared with a grid spacing of 7 km in the current operational system. AMM15 (Atlantic Margin Model, 1.5 km) is introduced as a new regional configuration of NEMO v3.6. Here we describe the technical details behind this configuration, with modifications appropriate for the new high resolution domain. Results from a 30 year non-assimilative run, using the AMM15 domain, demonstrate the ability of this model to represent the mean state and variability of the region.

Overall, there is an improvement in the representation of the mean state across the region, suggesting similar improvements may be seen in the future operational system. However, the reduction in seasonal bias is greater off-shelf than on-shelf. In the North Sea, biases are largely unchanged. Since there has been no change to the vertical resolution or parameterisation schemes, performance improvements are not expected in regions where stratification is dominated by vertical processes, rather than advection. This highlights the fact that increased horizontal resolution will not lead to domain-wide improvements. Further work is needed to target bias reduction across the North West Shelf region.

1 Introduction

The Met Office runs an operational ocean forecast for the European North West Shelf (NWS). This system is developed by both the Met Office and National Oceanography Centre, through the Joint Weather and Climate Research Programme. The current operational capabilities for the NWS are at a resolution of 7 km (O'Dea et al., 2017). While this configuration is able to reproduce the large-scale circulation across the shelf, it fails to resolve a host of dynamical features, such as mesoscale eddies, frontal jets, internal tides, and tidally rectified transport (e.g., Holt et al., 2017). All of these features make a substantial contribution to the fine scale currents and material distribution throughout the shelf seas. For example, mesoscale eddies can have a radius < 10 km on mid-latitude continental shelves, and are crucial in transporting heat, freshwater and nutrients in the region (e.g., Badin et al., 2009). To simulate these processes in numerical models, we therefore require higher resolution.

Across the NWS, the majority of previous high resolution studies (< 2 km grid spacing) have been limited to shelf regions (e.g., Holt and Proctor, 2008). These studies have shown the impact of resolution, for example resolving buoyancy-driven currents along tidal mixing fronts (Holt and Proctor, 2008), and cross-front transfer through baroclinic instabilities (Badin et al., 2009). However, using a purely on-shelf domain, these studies neglect the potential influence of shelf-break dynamics.

A recent study by Guihou et al. (2017) has demonstrated the potential impact of increased resolution across the NWS, using a domain that extends to $\sim 20°$W, comparable to the existing forecast system (O'Dea et al., 2017). With a resolution of ~ 1.8 km, internal waves are generated along the shelf break, as well as locally around bathymetric features on the shelf, such as sea mounts. Resolving such features has significant impacts on vertical mixing and stratification across the shelf, and therefore they need to be represented to make accurate ocean forecasts across the region.

The next generation ocean forecast model for the European NWS is introduced here, with the intention that it will become operational in 2018. The new configuration has a resolution of 1.5 km throughout the NWS domain. This will allow a step-change in our simulations, with the aim of improved representation of spatial and temporal variability. This configuration will typically be used to produce forecasts on time scales of hours to weeks. Surface products are made available on hourly to sub-hourly timescales (e.g. temperature, salinity, velocity and surface height), with full-depth products also available on hourly, daily and monthly timescales. The full operational system will include data analysis. This system may also then be used to produce decadal reanalysis products, similar to that produced for the existing operational domain (O'Dea et al., 2017).

Before the inclusion of data analysis, it is important to understand any underlying biases in the free-running model, along with potential model drift. Here we present a 30 year non-assimilative run, using the new high resolution domain. This long simulation demonstrates the ability of this model to represent the mean state and variability of the region. The existing operational system has known biases, outlined in O'Dea et al. (2017). We compare the results from this new simulation with the performance of the current system, to illustrate where there is likely to be the greatest improvements. Hereafter, the new 1.5 km domain will be referred to as AMM15 (Atlantic Margin Model, 1.5 km resolution). The existing operational model will be referred to as AMM7 (7 km resolution).

2 Model Development

2.1 Core Model Description

AMM15 is a regional configuration of NEMO (Nucleus for European Models of the Ocean), at version 3.6 stable (Madec, 2016). Compared with the current operational system (AMM7), this configuration has a new domain, at higher resolution (Figure 1). However, aside from the horizontal grid, AMM15 shares many features with the previous configuration, which has been described in O'Dea et al. (2012, 2017). Here we outline some of the key components and parameterizations. The horizontal resolution is sufficient for resolving the internal Rossby radius on the shelf, which is of order 4 km (Holt and Proctor, 2008). As such, only a minimal amount of eddy viscosity is applied in the lateral diffusion scheme, to ensure model stability. For momentum and tracers, bi-laplacian viscosities are applied on model levels, using coefficients of $6 \times 10^7\,\mathrm{m^4\,s^{-1}}$ and $1 \times 10^5\,\mathrm{m^4\,s^{-1}}$, respectively.

Tides are the dominant source of variability across the majority of the North West Shelf. A non linear free surface is therefore implemented using the variable volume layer (Levier et al., 2007). Time splitting is included, with a barotropic time step chosen automatically to satisfy a maximum Courant number of 0.8. For a baroclinic time step of 60 seconds there are then 17 barotropic time steps for each baroclinic.

The vertical coordinate system is based on a $z*-\sigma$ approach, as described in Siddorn and Furner (2013). The stretching function used here allows for more uniform surface heat fluxes across the domain, with the thickness of the surface cell set to ≤ 1 m. With terrain-following coordinates, large slopes between adjacent grid cells can lead to pressure gradient errors. To reduce such errors, vertical cells can be masked over slopes which exceed a specified value, r_{max} (where $r = (h_i - h_{i+1})/(h_i + h_{i+1})$, and $h_{i,i+1}$ are adjacent bathymetry points). Terrain following coordinates are fitted to a smoothed envelope bathymetry, with the level of smoothing based on the chosen r_{max} value. In regions where the smoothed model levels become deeper than the input bathymetry, these levels are then masked. The r_{max} value was here chosen to be 0.1. This is a lower value than used in previous configurations. However, with increased resolution, the model bathymetry is rougher, resolving steeper gradients and canyons along the shelf-break. This value was then chosen to ensure stability in the configuration, without the need to smooth the input bathymetry.

For AMM15, there is no increase in the vertical resolution, using 51 vertical levels. The vertical parameterizations in AMM15 then remain similar to the current operational system. The Generic Length Scale scheme is used to calculate turbulent viscosities and diffusivities (Umlauf and Burchard, 2003). Surface wave mixing is parameterized by Craig and Banner (1994). A minimum surface roughness is specified as 0.02 m. Dissipation under stable stratification is limited using the Galperin limit (Galperin et al., 1988) of 0.267 (Holt and Umlauf, 2008). Bottom friction is controlled through a log layer with a non-linear drag coefficient set at 0.0025.

2.2 Domain and Bathymetry

The domain for AMM15 has a smaller area than the current operational domain (Figure 1). This is due to the computational demands of higher resolution, considering both ocean-only as well as future coupled simulations. The model domain extends from approximately $45°$N to $63°$N, with a uniform grid spacing of ~ 1.5 km in both the zonal and meridional direction. Compared to AMM7, the number of wet cells has increased by a factor of ~ 15. While the operational run time is still uncertain (pending future developments), the physics only AMM15 configuration requires approximately 400 node hours per day, compared to 20 node hours per day for AMM7. The storage costs have also increased (by a factor of ~ 11 for standard daily output files).

The domain boundaries were chosen carefully, to ensure that they would not limit representation of major current pathways, whilst also ensuring that the grid would be compatible with coupled simulations (e.g. considering location of mountain ranges and the Mediterranean within the domain used for ocean-atmosphere coupling) (Lewis et al., 2017). This chosen common domain is now also in use at the Met Office for uncoupled operational UK weather forecasts (extending the existing operational domain, e.g., Tang et al. (2013)). To the south, the AMM15 boundary was chosen far enough north of the Spanish coast, so that the shelf-break transport could flow into the domain perpendicularly through the relaxation zone (rather than parallel to the

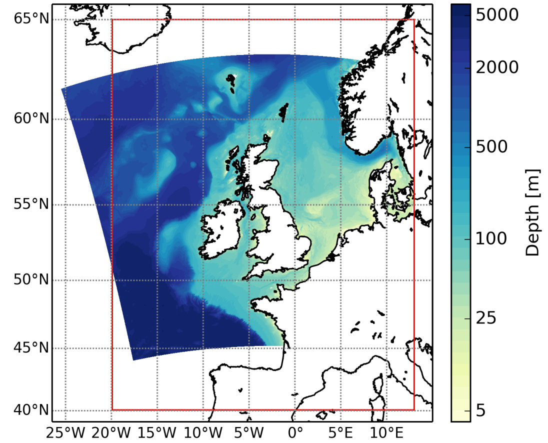

Figure 1. Map illustrating the location and bathymetry of the model domain (indicated by the shaded region). Shading shows bathymetry from EMODnet [m] (note logarithmic scale). Red line illustrates the extent of the current operational domain, AMM7 (7 km resolution).

boundary), while considering placement in relation to the Gironde Estuary. The northern boundary is placed sufficiently north of the Faroe Islands, to allow transport around the islands, but far enough south to not be concerned with the representation of overflows or transport around Iceland. The representation of overflows is a longstanding known problem in lower resolution global models (e.g., Beckmann and Döscher, 1997; Roberts and Wood, 1997). Given that lower resolution data (O(1/4°)) will be used as boundary conditions for this regional model, it is advisable to avoid the overflow region with the domain. To the west, the model extends far enough into the Atlantic to allow off-shelf dynamics to develop away from the shelf-break, reducing potential impacts of boundary conditions on shelf-break exchange. To the east, the boundary remains in the Baltic, similar to previous versions. However, since the increased resolution allows for potentially improved representation of heat and freshwater transport through Danish Straits, the boundary is now placed at $\sim 12°$E, in the Arkona Basin, rather than within the ~~Kattegat~~Kattegat, north of the Danish Straits.

The bathymetry chosen for AMM15 is EMODnet (EMODnet Portal, September 2015 release). This product was the best available at the time, combining all observations from the region. With increased resolution, increased detail can now be represented in the model's bathymetry. For numerical models, the limitation is that the EMODnet product is referenced to lowest astronomical tide (LAT), whereas the model requires bathymetry referenced to mean sea level (MSL). In the deep ocean this is less of a concern, since the range of the tide is negligible compared with the depth of the ocean. However, this difference is crucial when considering the depth along shallow coastal regions where there are large tidal ranges. To apply an adjustment from LAT to MSL, we have used an estimate of the LAT from a 19 year simulation of the CS3X tidal model (Batstone et al., 2013). For each point, the lowest tidal depth has then been added to the original EMODnet depth.

EMODnet data is provided with a land sea mask based on OpenStreetMap (2014), which has here been interpolated onto the AMM15 grid. EMODnet data is originally obtained at a higher resolution than AMM15. For grid cells of partial land/sea, they were originally set as land if the EMODnet land mask covered $> 50\%$ of the target grid cell. Following this interpolation, the mask was assessed manually to check the representation of narrow channels, estuaries or small islands. This simulation does not include wetting and drying, so the land sea mask is fixed, and a minimum depth is specified for the input bathymetry. Taking into account the large tidal ranges in the Bristol Channel and Gulf of St. Malo, this minimum depth is specified as $10\,\mathrm{m}$. While the tidal range may be smaller in other regions, this domain-wide minimum depth was chosen for simplicity, as well as consistency with previous configurations. Wetting and drying is not available within NEMO vn3.6, however it is currently under development for NEMO vn4.0. This capability will then be a priority for future development of AMM15.

2.3 Forcing and Initialisation

The simulation discussed here covers 30 years, starting in 1985. This is a free running simulation, with no data assimilation. During this time, the regional model is forced with lateral ocean boundary conditions, surface atmospheric forcing, river runoff and tidal forcing.

All lateral boundary conditions except the eastern boundary have been taken from a series of global ocean simulations, carried out with the ORCA025 configuration at the Met Office. ~~For operational purposes, boundary conditions will be derived from a $1/12°$ configuration of the North Atlantic (NATL12). However, this NATL12 data is not available over a sufficient time period be used for this long hindcast. For~~ For 1985-1989, the boundaries used here come from a free running global ocean hindcast (Megann et al., 2014). This same simulation provided the initial temperature and salinity conditions for the AMM15 hindcast, with the model initialised from rest on 1^{st} January 1985. For 1990 onwards, the boundary conditions are taken from the Global Seasonal Forecast System (GLOSEA), version 5 (MacLachlan et al., 2015; Jackson et al., 2016), which includes assimilation of both satellite and in situ observations, where available. Analysis of AMM15 will therefore focus on the period of GLOSEA forcing, allowing a 5 year spinup period prior to this date. For the eastern boundary, conditions have been taken from a regional Baltic simulation (Gräwe et al., 2015). This alternative data set was chosen due to the increased resolution ($1/60°$, as opposed to $1/4°$ in the ORCA025/GLOSEA data), in order to resolve flow through the Arkona Basin ($\sim 12°$E).

For operational purposes, alternative boundary conditions will be used for both the Baltic and Atlantic boundaries. For the Atlantic, these will be derived initially from a $1/12°$ configuration of the North Atlantic (NATL12). For the Baltic, boundary forcing will be provided from operational forecast products available through the Copernicus Marine Environmental Monitoring Service. However, neither of these data sets are available over a sufficient time period be used for this long hindcast.

From each of ~~these~~ the chosen data sets, the model boundary was forced with 3D temperature and salinity fields, barotropic velocities, and sea surface height (SSH). For SSH, the global data fields were corrected to remove drift from the free-running 1985-1989 simulation, and then ensure that there was no jump between this and the following data sets. Following the same method outlined in O'Dea et al. (2017), an offset was also applied to the global data to ensure that the mean SSH over this domain was approximately zero. For the Baltic boundary, a different offset was applied to ensure that the mean SSH across the boundary matched what would have been present in the GLOSEA forcing. This maintains the variability present in the Baltic data, but avoids any SSH difference relative to the other boundaries that might result in anomalous transport into or out of the eastern boundary.

Tidal ~~forcing~~ potential is calculated across the domain for 12 constituents. In addition to this, tidal forcing is applied along the lateral boundaries. Forcing has been applied using the Topex Poseidon crossover solution (Egbert and Erofeeva, 2002), TPXO7.2, Atlantic Ocean 2011-ATLAS. ~~This is obtained at a resolution of 1/~~For each of the 12 ~~°. The~~ constituents, amplitude and phase ~~is provided for 12 tidal consituents~~ (surface height and velocity) ~~.~~ was obtained at a resolution of $1/12°$.

River runoff is based predominantly on a ~~climatology of daily~~ daily climatology of gauge data, averaged for 1980-2014. UK data was processed from raw data provided by the Environment Agency, the Scottish Environment Protection Agency, the Rivers Agency (Northern Ireland) and the National River Flow Archive (gauge data were provided by pers. comm from Dr. S. M. van Leeuwen, CEFAS, Lowestoft, UK). For major rivers that were missing from this data set (e.g. along the French and Norwegian coast), data has been provided from an earlier climatology (Young and Holt, 2007; Vorosmarty et al., 1998). For each river ~~, the specified depth of~~ point, a daily freshwater flux is specified with the depth dependent on the average ratio of runoff to tidal range ~~,~~ (based on estuary classifications discussed in Cameron and Pritchard (1963)~~.~~). The runoff temperature is assumed to match the local SST, with no temperature data included in the climatology.

Atmospheric forcing is taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis product, ERA-Interim (Dee et al., 2011). This ~~forcing~~ has a spectral resolution of T255 ($\sim$ 79 km).The operational system will make use of the higher resolution ECMWF Numerical Weather Prediction model (0.125° resolution). Forcing is applied using the CORE bulk forcing algorithm (Large and Yeager, 2009), for the full 30 years of the simulation. All variables are applied at 3-hourly intervals. Light attenuation is set to the standard NEMO tri-band scheme (RGB), assuming a constant chlorophyll concentration of $0.05\,\mathrm{mg\,g^{-3}}$ (Lengaigne et al., 2007).

2.4 Summary of differences between AMM7 and AMM15 simulations

For comparison with the existing operational configuration (AMM7), the results from this long hindcast are compared with the AMM7 hindcast discussed in O'Dea et al. (2017). While the construction of these NEMO configurations is similar, there are some differences between the chosen model parameters and boundary conditions. The key differences are outlined here.

The AMM7 hindcast spans 1981-2012, with boundary conditions from both ORCA025 and GLOSEA. The simulations used to initialise and force AMM7 differ to those used for AMM15~~, however the period~~ . As with AMM15, the period prior to 1990 has been forced with a free-running simulation, which also provided the initial conditions for January 1981. However, the period of GLOSEA forcing (post-1990) should be relatively similar, given that data assimilation has been included in the boundary conditions. Analysis of model climatology will then focus on a common 20 year period in both simulations, 1991-2010.

With 7 km resolution, no attempt was made to model the Danish Straits. The Baltic boundary was placed north of the Straits, with temperature and salinity relaxed to climatology during the CO5 hindcast. No barotropic forcing was applied at this boundary.

In addition to the differing horizontal resolution and spatial coverage between the AMM15 and AMM7 domains as seen in Fig. 1, the source bathymetry for AMM7 is derived from the much coarser North-West Shelf Operational Oceanographic System (NOOS) dataset. Not only are fine scale features missing from the NOOS bathymetry, but there are significant differences in mean depth in some on shelf regions of the North Sea.

The fresh water riverine input also differs. Instead of the climatology used in AMM15, in AMM7 the rivers were based upon the European version of the hydrological model HYdrological Predictions for the Environment (E-HYPE, version 2.1) (Donnelly et al., 2015). Use of this data allows for potential interannual variability in fresh water fluxes, however fresh water biases in areas such as the German Bight in AMM7 have been attributed to large riverine flux from E-HYPE (O'Dea et al., 2017). The mean total freshwater input from E-HYPE v2.1 was found to be $\sim 18\%$ larger than the climatology. This forcing data was then not chosen for AMM15.

The source of the tidal forcing also differs. AMM7 uses tidal forcing derived from a model of the North Atlantic (Flather, 1981) in contrast to TPXO7.2 data utilized in AMM15.

3 Model Comparison and Validation

3.1 Tidal harmonics

A large proportion of the model performance across the shelf can be determined by tides. Figure 2 shows the co-tidal plot of the M2 constituent for both AMM15 and AMM7. Both models show a very similar pattern, with good agreement in terms of the location of amphidromes across the shelf. There is a slight shift in the position of the amphidrome off the northern Irish coast, towards Scotland. In the English Channel, there is also a slight shift to the west of the Isle of Wight. At both these locations, this coincides with reduced errors in amplitude and phase in AMM15.

The mean bias and ~~RMSE~~ route-mean-square error (RMSE) of major constituents, compared with available tide gauge observations (from NOC Marine Data Products and BODC), is presented in Table 1. For the phase of each constituent, the RMSE is reduced in AMM15. The mean bias is reduced for 4 out of the 7 constituents shown. AMM15 amplitudes show less improvement. The RMSE for most constituents is of the same order in both configurations, with the exception of M4. However, both M2 and M4 show an increased mean bias in AMM15, compared to observations. A summary of errors in the semi-major axis of tidal currents is also presented in Table 1 (analysis follows the same method used in Guihou et al. (2017)). Again, the RMSE and bias are found to be of a similar magnitude in the two configurations, but with a slight increase in both M2 and M4. For M2, positive anomalies in surface height can be seen in particular along the east coast of the UK, and on the west coast of England, in the Irish Sea (Figure 2c,d). The increased mean bias can be partly accounted for by the fact that errors are more uniform across the domain. For AMM7, while the RMSE has a similar magnitude to AMM15, compensating errors in both amplitude and phase are found around the UK, reducing the apparent mean bias.

While the overall performance of AMM7 and AMM15 are similar (Table 1), anomalies vary across the domain, showing regional improvements. For example, there is particular improvement in the English Channel in AMM15 for both amplitude and phase (figure 2c-f). The amplitude of M2 also has reduced errors off the west coast of Scotland~~.~~, particularly around the

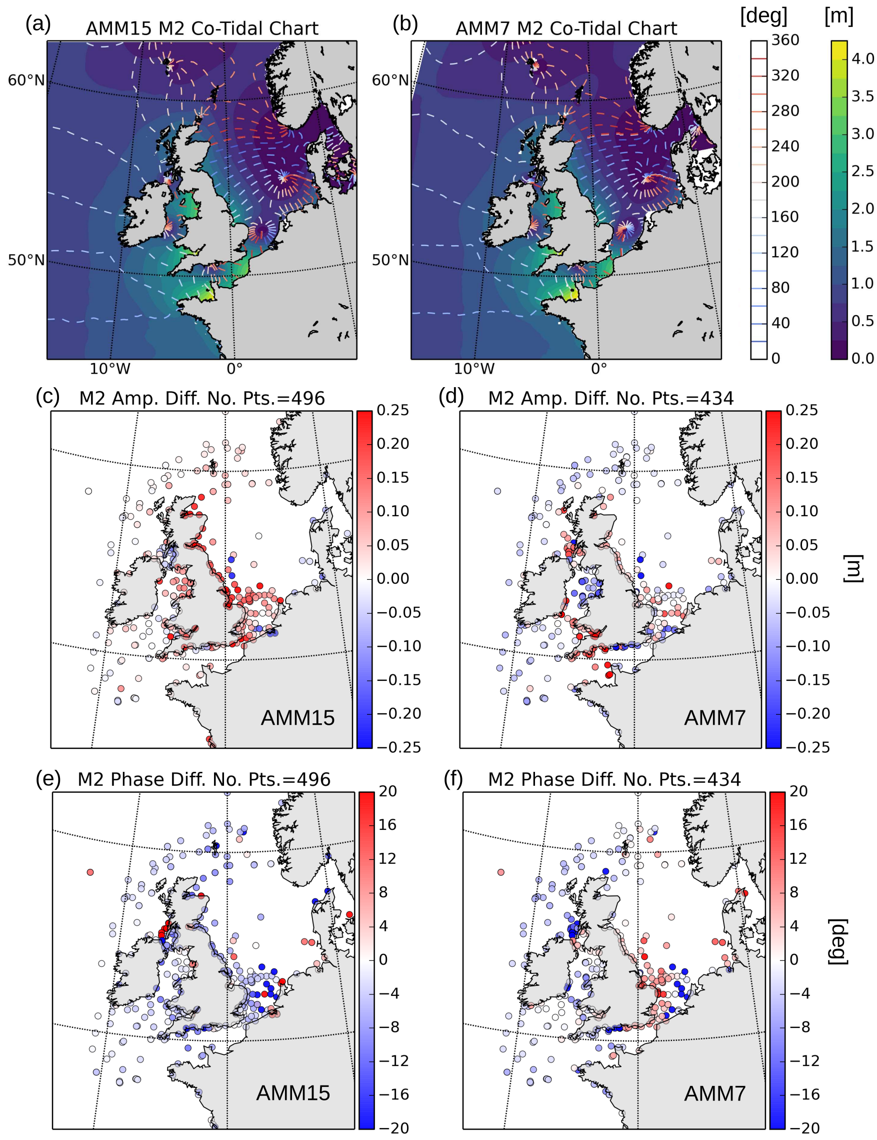

Figure 2. Top panels show M2 Co-tidal plots for AMM15 (a) and AMM7 (b). Shading shows M2 amplitude [m]; dashed contours show the phase [deg]. Lower panels show errors in amplitude (c-d) and phase (e-f) for the M2 constituent of the two configurations (model - observations). Observations are tide ~~gauge~~ gauges data ~~obtained~~ from National Oceanography Centre (NOC) Marine Data Products and the British Oceanographic Data Centre (BODC). The number of valid observations (N) is shown for each constituent comparison, depending on the land-sea mask represented in each model configuration. .

Kintyre Peninsula. There is a considerable difference in the resolution of the coastline between these configurations, which will have a large impact in these regions.

Table 1. Mean bias and RMS error (model minus observations) for amplitude and phase of major tidal constituents, as well as the semi-major access of tidal currents. Observations are tide gauges data from National Oceanography Centre (NOC) Marine Data Products and the British Oceanographic Data Centre (BODC). Tidal current analysis uses the same data and method outlined in Guihou et al. (2017). The number of valid observations (N) is shown for each constituent comparison, depending on the observed variable and land-sea mask represented in each model configuration.

	Amplitude [cm]		Phase [deg]			Current [cm s^{-1}]		
Constituent	RMSE	Bias	RMSE	Bias	N	RMSE	Bias	N
AMM15								
M2	12.641	6.277	10.865	-3.664	496	10.307	5.368	116
S2	5.042	2.515	12.243	-4.108	495	3.586	1.908	116
K1	1.820	0.836	15.102	-2.361	495	0.824	0.310	114
O1	1.502	0.344	13.427	-2.048	494	0.747	0.160	114
N2	4.150	0.936	22.340	-1.279	497	2.523	0.625	112
Q1	1.272	-0.241	33.227	1.835	455	-	-	-
M4	8.043	3.148	59.550	-10.215	460	1.525	0.230	113
AMM7								
M2	11.797	0.423	12.244	-1.864	434	8.895	4.094	115
S2	4.589	1.612	13.243	-1.351	434	3.634	1.847	115
K1	1.642	0.538	19.933	-5.051	432	0.936	0.307	114
O1	1.769	-0.969	23.187	-2.926	434	0.621	-0.182	114
N2	4.203	0.748	26.084	0.947	435	2.419	0.648	112
Q1	1.817	1.007	42.761	15.080	390	-	-	-
M4	4.879	0.666	84.992	12.721	395	1.224	-0.033	113

One factor which must be taken into account is that the model applies a minimum depth of 10 m, due to the absence of wetting and drying. The same minimum depth is applied here as in previous configurations. The speed at which the tide travels, and hence the phase of constituents, is dependent on water depth. Hence, while the coastline has been improved, errors are expected due to the depth in shallow coastal regions. This difference in depth will have a large impact in regions such as the East Anglian coast and the Wadden Sea, in the Southern North Sea, as well as shallow estuaries, such as the Bristol Channel, Morecambe Bay and Solway Firth.

There are complex interactions between water depth and the simulation of tidal constituents. The dependency on depth for shallow water wave speed suggests that the simulated speed would be higher with an imposed minimum depth, compared with observations. However, any change in tidal currents will have impacts on the level of bottom friction that is felt, and there may also be wider impacts on resonance and amplitude across the shelf. Therefore, impacts on tidal circulation are expected to be found downstream of any apparent depth anomalies, as well as more widely across the domain. For AMM15, the M2 constituent shows a negative bias in phase (consistent with increased speed) and positive bias in amplitude (Table 1), with

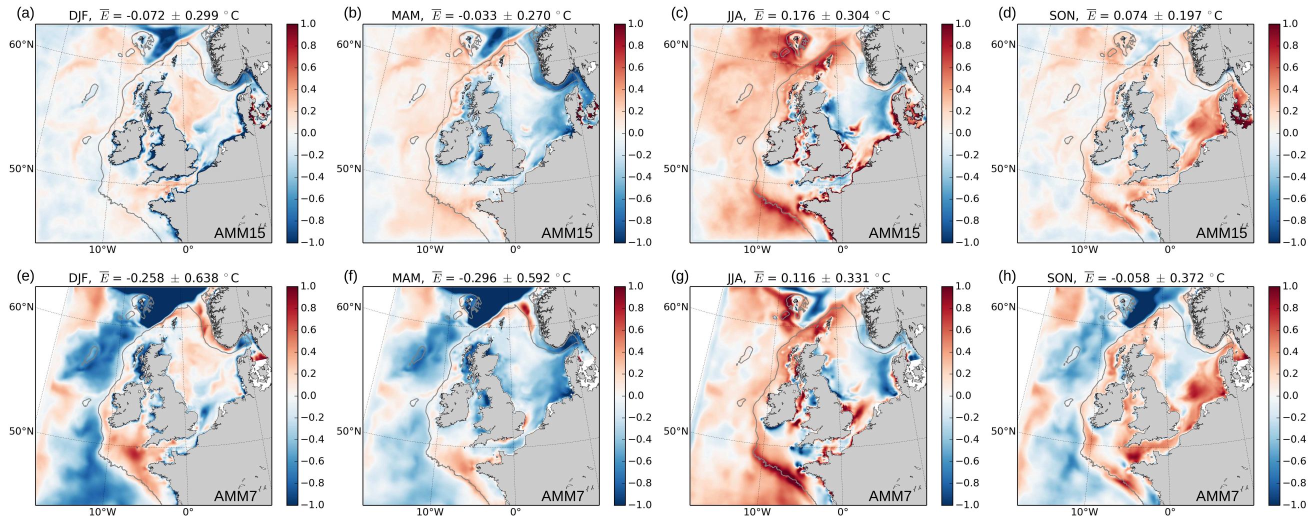

Figure 3. Seasonal SST anomalies for model minus observations [°C]. ~~All panels show 20 year-mean anomalies, for period 1991-2010.~~ Observations used are OSTIA CCI reanalysis product (Merchant et al., 2014) (NB. OSTIA CCI product only available from Sep 1991). All panels show 20 year-mean anomalies, for period 1991-2010, with anomalies calculated as $\overline{SST_{AMM}} - \overline{SST_{OSTIA}}$. Upper panels (a-d) show anomalies for AMM15-OSTIA, lower panels (e-h) show anomalies for AMM7-OSTIA. Mean errors ($\overline{E}$) and standard deviations are calculated spatially for the region shown (excluding wider AMM7 domain). Grey contour shows the 200 m isobath, to indicate the limit of the continental shelf.

anomalies larger along the east coast of the UK (Figure 2c). Both models show reduced anomalies off-shore, towards the shelf break, although this reduction appears greater for AMM15 than AMM7.

For AMM7, while there are similar limitations with minimum depth, the coarse coastline may have led to compensating errors in the phase and resonance of tides throughout the region (and hence reduced mean bias). As this configuration has been in operational use for a number of years, the coastline has also been modified to ensure the best possible representation of tides, e.g. deepening or widening channels as required. For AMM15, the initial aim has been to ensure the most realistic coastline possible. It is therefore encouraging to see that overall there is a comparable if not improved representation of the majority of constituents, despite the considerable differences between both the domains and forcing.

Wetting and drying is currently under development for NEMO vn4.0, with the hope of implementation in future configurations. This would enable ‘realistic’ depths to be included in the model.

3.2 Surface Climatology

Figure 3 shows the mean sea surface temperature (SST) anomalies over the model domain compared with observations, for both AMM15 and the previous operational model. Observations used are a reanalysis version of the Met Office Operational

Sea Surface Temperature and Sea Ice Analysis (OSTIA), produced for the European Space Agency's Climate Change Initiative (CCI) (Merchant et al., 2014). This analysis provides a 20 cm SST product, and is therefore useful for comparing to the uppermost SST in ocean models. Both models show varying biases during the seasons. Overall the standard deviation of anomalies in AMM15 is reduced compared with AMM7. The largest difference between the two models is found in the north of the domain, where AMM15 is substantially warmer than AMM7, and hence has a reduced cold bias. This cold bias in AMM7 was found to originate from the north western boundary of the domain, near the Iceland coast (O'Dea et al., 2017). The reduction of the cold bias here is then likely related to the change in the location of the boundary. AMM7 has its largest mean SST anomalies in winter ~~and spring~~(DJF) and spring (MAM), with a cold bias dominating off-shelf. Analysis of the monthly mean anomalies (not shown) indicates that the cold bias grows progressively during these seasons, reaching a peak in April of -0.356 ± 0.643 °C.

Off-shelf, AMM7 was found to alternate between a cold bias in the winter months and warm bias in the summer (JJA) (O'Dea et al., 2017). For AMM15 the model has relatively small bias off-shelf for the majority of the year, with the exception in JJA when a similar warm bias remains. For AMM15, the largest mean bias occurs in this season, with a mean error of 0.176 ± 0.304°C (compared with 0.116 ± 0.331°C for AMM7). This warm bias peaks in July, when there is a mean anomaly of 0.230 ± 0.334°C across the domain. This bias may in part be related to ~~overstratification~~over-stratification, or limitations of the uniform RGB light attenuation. Both these models use similar vertical mixing schemes, and light attenuation scheme. The choice of light attenuation scheme, and potential impacts on stratification, will be discussed further in Section 3.3.

Over the continental shelf break, there is still a warm bias compared with observations during the summer (Figure 3). However, this warm bias has been reduced in AMM15 compared with AMM7. Over the shelf break, the mean SST is typically lower than the surrounding ocean during the summer due to increased vertical mixing. The generation of internal tides at this location provides energy for increased mixing as the internal waves break. This reduces the surface temperature due to mixing with the cooler water beneath the pycnocline. At 1.5 km resolution, internal waves begin to be resolved in the model (as discussed in Guihou et al. (2017)). These processes are not resolved at 7 km resolution. Therefore, AMM15 has increased mixing above the shelf break, contributing to reduced SST in this region. There is still a warm bias in this region, in particular to either side of the shelf break itself. This suggests that AMM15 may not be resolving the full extent of the internal waves, and their impact on vertical mixing.

In the Norwegian Trench, there is a strong cold bias during the spring (Figure 3). In the Baltic, there is a warm bias during Autumn (SON). The anomalies in this region are at times larger than those in AMM7, however there have been significant changes to the Baltic boundary conditions between the two models. Aside from the change in location, AMM15 also has the addition of SSH and barotropic currents forcing at the boundary (where there was none in AMM7). Therefore, we may expect significant changes in transport ~~into and out of this~~ through the region, which would affect the Norwegian Trench heat and salt transport.

On the shelf, the biases in the two models remain similar. For example, across the North Sea both models show a similar pattern of cool bias during spring-summer, followed by a warm bias in autumn (Figure 3). The warm bias is particularly strong in the southern North Sea, around the German Bight. There are a number of potential causes for these biases. Initially, there

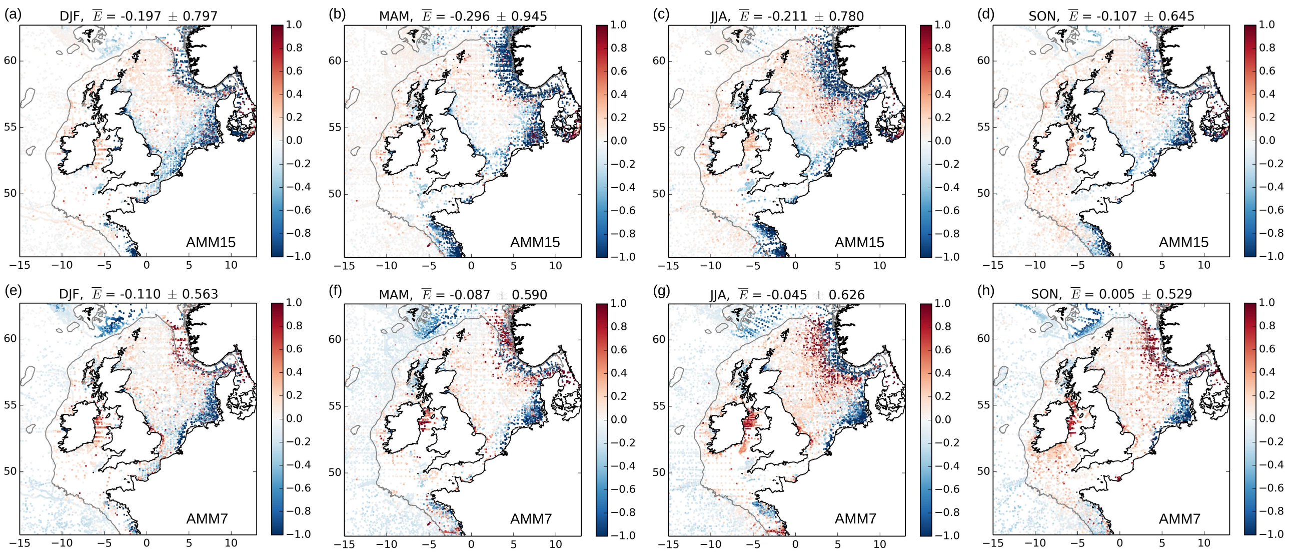

Figure 4. Mean seasonal SSS anomalies for model minus observations. Observations used are monthly-mean EN4 profiles (Good et al., 2013). Upper panels (a-d) show anomalies for AMM15-EN4, lower panels show anomalies for AMM7-EN4 (e-h). All panels show monthly anomalies averaged over the period 1991-2010. Mean errors ($\overline{E}$) are calculated for the AMM15 domain region (excluding the wider AMM7 domain). Grey contour shows the 200 m isobath, to indicate the limit of the continental shelf.

could be errors in the surface heat fluxes from ERA-Interim, used to force both simulations. If the assumed SST in ERA-Interim differs to that of OSTIA, then this will be a limiting factor in the ability of the model hindcast to reproduce the observed SST. However, these SST anomalies may also be related to thermal inertia within the ocean, with a lag in the loss or gain of heat through the seasons. Under the same surface heat flux, it will take longer to heat (and cool) a fully mixed water column, than a shallow, stratified surface layer. This may then be related to weak stratification across the shelf. In shallow coastal regions (which are already fully-mixed), the 10 m minimum depth could also be a contributing factor. Another likely source of error is the light attenuation scheme. Across the shelf, the uniform light attenuation will overestimate the depth of light penetration. This may lead to an increase in heat content in the deeper ocean, and hence the ocean will take longer to cool as the mixed layer deepens in the autumn. During spring and early summer, if solar heating isn't concentrated within a shallow surface layer (as may occur across a spring chlorophyll bloom), then the heat flux will be distributed with depth and the surface temperature will take longer to increase.

In other coastal regions, anomalies can be found which may be related to over stratification. For much of the British coastline, there are cold anomalies in the winter months, and warm anomalies in the summer. The location of these anomalies is consistent with the location of fresh biases in the surface salinity, which will be discussed below (Figure 4). Further analysis of the stratification in the model will be discussed in the following section (Section 3.3).

Figure 4 shows the surface salinity (SSS) biases, for AMM15 and AMM7 compared with EN4 profiles (Good et al., 2013). There is improvement in the north of the domain, with a reduced fresh bias in AMM15. As discussed in relation to the SST biases, this is likely related to the northern boundary conditions.

One region where AMM15 performs worse than AMM7 is in the Norwegian Trench. There is a fresher anomaly here than in the coarser model. Within the Norwegian Trench, fresh Baltic water is found traveling north on the eastern side. Low salinity is also maintained northwards with the addition of river runoff along the Norwegian coast. On the western side of the Trench, warm saline Atlantic Water flows southward. At the boundary between these two water masses, instabilities and eddies may form, encouraging mixing of properties across the Trench. Previous analysis of AMM7 has shown a dipole across the trench - too fresh along the coast, and too saline off-shore (e.g. Figure 4g). This was believed to be due to a lack of lateral mixing across the Trench. In AMM15, there is no longer a saline bias offshore, consistent with an increased eddy activity in the region. However, there is a stronger fresh bias throughout the trench, extending from the Baltic Sea. This contributes to an increased mean fresh bias over the AMM15 domain.

Further work is needed to attribute this fresh bias within the Norwegian Trench. The Baltic boundary has been altered between the two models, with a significant change in position as well as forcing methods. Such changes would likely have a large impact on the transport into or out of the Baltic. However, the position and forcing along the Atlantic boundaries has also changed, with potential impacts on the balance of transport within the Trench. Further experiments are needed to be able to attribute anomalies to either of the new boundary locations or forcing products. Changes in any salinity bias may also be influenced by local river runoff as well as the large scale transport.

Elsewhere there has also been a freshening close to the coast (Figure 4). The river fluxes have been altered between the two models. Overall the climatology has a reduced total freshwater input compared with E-HYPE. However, in some regions, such as along the British and Irish coast, the mean runoff is higher in the climatology (O'Dea et al., 2017). Comparing the conditions in the southern North Sea, AMM15 is fresher than AMM7. However, the sign of anomalies along the coast can vary. In places there is a dipole where AMM15 is fresher at the coast and more saline off shore (Figure 4). This suggests that AMM7 may be more diffusive within river plumes, for example allowing freshwater input from the Rhine to be advected off-shore, whereas AMM15 keeps a narrower plume close to the coast. Indeed, the lateral diffusion prescribed in AMM15 is lower than that used in AMM7, due to the increased resolution and hence ability to resolve mesoscale processes on the shelf (Section 2.1). While $1.5\,\mathrm{km}$ is not sufficient to fully resolve plume dynamics, this response is consistent with previous studies on the impact of resolution for plume dynamics (e.g. Bricheno et al., 2014). A similar dipole response can be seen in the SST, indicating a change in stratification in the region, associated with the shift in position of the river plume.

3.3 Seasonal Stratification

With the onset of stratification in spring-summer, tidal mixing fronts form a key part of the shelf hydrography. The position of these fronts is dependent on the balance between tidal energy and strength of stratification. Assuming a uniform rate of heat input, the location of the fronts is then shown to be dependent on the tidal velocity and depth of the water column (Simpson and Hunter, 1974). Figure 5 shows the location of tidal mixing fronts in AMM15 and AMM7, compared with ob-

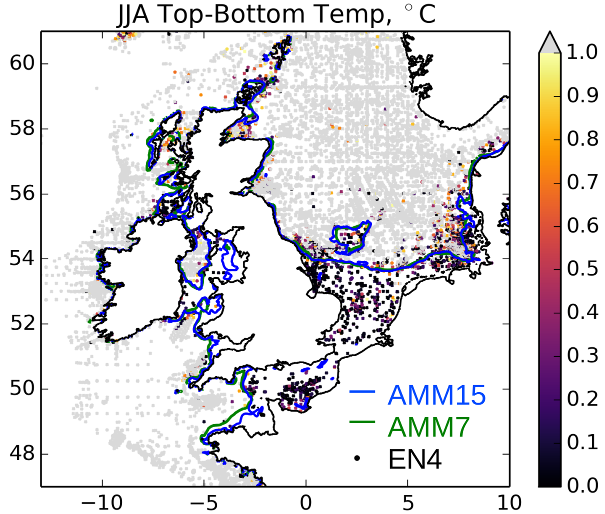

Figure 5. Mean summer stratification, indicated by top-bottom temperature difference [$^\circ$C]. Blue and green lines contour regions with a mean top-bottom temperature difference of 0.5°C in AMM15 and AMM7, respectively. Model results show the seasonal mean (JJA) for 1991-2010, indicating location of seasonal tidal mixing fronts. Shading shows the observed temperature difference (top-bottom), from all monthly-mean EN4 profiles during 1991-2010 (Good et al., 2013). Points showing $> 1^\circ$C are coloured grey for clarity.

served stratification. This shows that across the majority of the shelf, the fronts are found in a similar location in both models, and compare well with observations. Similarity between the models is consistent with the fact that both have similar representations of the major tidal constituents, and have similar vertical mixing schemes. However, there are improvements in the position of fronts in the western Channel, as well as the west coast of Scotland. This is consistent with the reduced amplitudes (and hence reduced errors) of M2 seen in Figure 2. Aside from improved representation of the coastline in AMM15, there are also differences between the bathymetry used in AMM15 (EMODnet) and AMM7 (NOOS). In particular, there is an average increase in water column depth off the west coast of Scotland, of the order of 20 m. Partly this may be due to the use of a more recent, improved bathymetric product, based on increased number of available observations. The increased resolution will also allow deep channels between islands to begin to be resolved. This increased depth can then prevent the water column from being fully mixed during the summer months.

Figure 6 shows mean vertical profiles for temperature and salinity during summer for stratified regions across the continental shelf. In the North Sea (Region 1), there is a cool bias at the surface along with a warm bias at depth (Figure 6a,g). There are a number of factors that could influence anomalies across the shelf, including errors in surface fluxes, or advection into or out of the region. Vertical profiles will also be strongly influenced by vertical mixing and light attenuation schemes. While the horizontal resolution has been increased in AMM15, there has been little change in the vertical resolution or parameterisation schemes. Therefore it is unsurprising that similar biases remain in the vertical profiles and stratification, as indicated by a

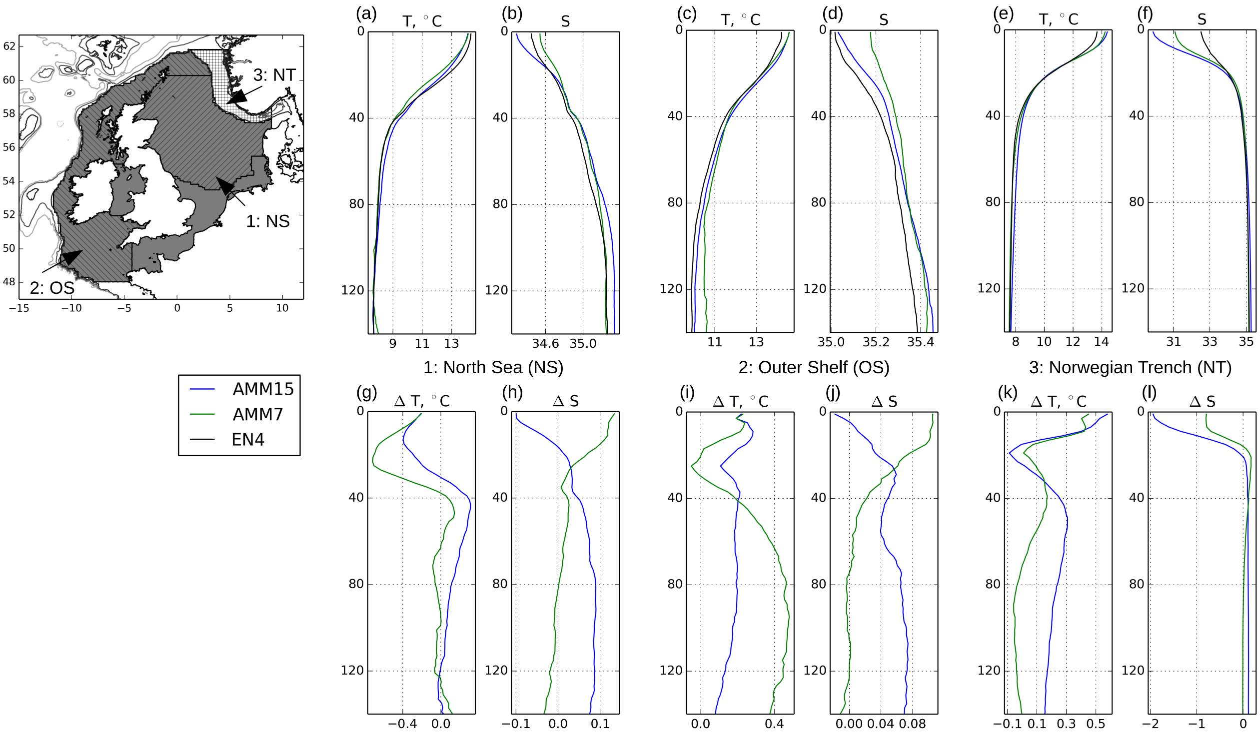

Figure 6. Mean summer (JJA) temperature [°C] and salinity profiles for three stratified regions, shown as hatched regions in the upper left panel: North Sea (NS), Outer Shelf (OS) and Norwegian Trench (NT). All panels show 20 year-mean profiles, for JJA, 1991-2010. Observations (black) are monthly EN4 profiles (Good et al., 2013). Upper panels (a-f) show mean profiles with depth, lower panels (g-l) show anomalies with depth for respective profiles, where $\Delta T = \overline{(T_{AMM} - T_{EN4})}$. Results from AMM15 and AMM7 are shown in blue and green, respectively.

similar surface bias in the region (Figure 3). The warm anomaly at depth during the summer (Figure 6g) will contribute to a warm surface bias during autumn, following the breakdown of stratification (Figure 3d,h).

Contrary to the North Sea, the outer shelf (Region 2, Figure 6c,i) shows a surface which is too warm. This may be related to the warm surface bias that does still exist along the shelf break (Figure 3c), due to a lack of vertical mixing in this region. Comparison with salinity profiles confirms that the surface is too fresh, whereas the deeper ocean is more saline than observed (Figure 6d,j). For AMM15, the warm bias decreases with depth, with reduced bias compared to AMM7 (Figure 6i).

Figure 7 shows the summer bottom temperature anomalies for both AMM15 and AMM7, compared with EN4 observations. This demonstrates that both models have a warm bias throughout the North Sea. However, anomalies in bottom temperature vary spatially. The mean profiles for the North Sea and outer shelf (Figure 6g,i) show a warm anomaly at depth, consistent with the mean bias shown in Figure 7. However, along the shelf break, AMM7 has a cold bias in bottom temperatures, consistent

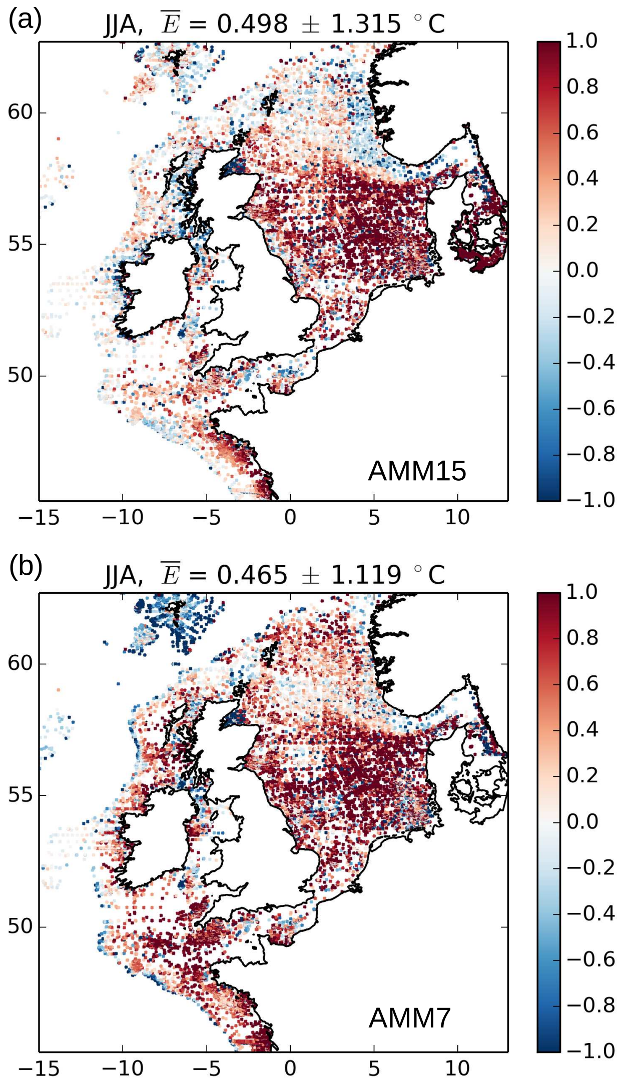

Figure 7. Mean seasonal bottom temperature anomalies for model minus observations [°C]. Both panels show 20 year-mean seasonal anomalies, for summer (JJA), 1991-2010. Observations used are monthly EN4 profiles (Good et al., 2013). Upper panel (a) shows anomalies for AMM15-EN4, lower panel (b) shows anomalies for AMM7-EN4. Mean errors ($\overline{E}$) are calculated for the AMM15 domain region, where bathymetry $< 500\,\mathrm{m}$.

with a lack of vertical mixing. It is also worth noting that since the depth across the shelf varies (from $\sim 20-200\,\mathrm{m}$), the anomalies shown in bottom temperature will not necessarily correspond to the base of the mean vertical profiles shown. For example, Figure 6g shows a maximum temperature anomaly in AMM15 at $40-50\,\mathrm{m}$. The largest anomalies in Figure 7 are found towards the shallower southern North Sea and coastal regions (Figure 1).

For AMM15, the bias in bottom temperature is reduced approaching the shelf break (Figures 6i and 7). This suggests that in regions with a greater influence from the open ocean, AMM15 performs better than the current configuration. This may be a result of AMM15 having improved representation of shelf-break processes, or reduced off-shelf biases, which would both influence biases in this region. The mean bias ($\overline{E}$) shown in Figure 7 does not appear reduced at higher resolution. However, this includes an increased warm bias in the Baltic for AMM15, outside the AMM7 domain. Excluding these points outside the AMM7 domain, AMM15 is then shown to have a reduced bias compared to AMM7, of 0.366 ± 1.001°C compared to 0.465 ± 1.119°C, respectively.

~~Given the biases that exist in stratification , it is~~ Overall, while there have been some improvements in AMM15, similar biases remain in stratification across the shelf. Given that both models have the same number of vertical levels, vertical mixing schemes, and surface forcing, this result is not entirely surprising. Across large areas of the shelf, the climate will be predominantly driven by a balance of vertical forces (surface buoyancy fluxes and vertical mixing) rather than horizontal advection. It is therefore clear that further work is needed to improve ~~vertical processes in this configuration~~the representation of these vertical processes. However, given that there are spatially varying anomalies across the shelf, the response to altering available parameters will vary. Improving the choice of vertical mixing schemes is still an active topic of research (Luneva et al., 2017), and the aim would be to improve those used in future operational systems.

Previous studies have assessed the impact on stratification of using an alternative light attenuation scheme (O'Dea et al., 2017). The uniform RGB scheme used here assumes a Chlorophyll concentration of $0.05\,\mathrm{mg.Chl\,m^{-3}}$ (Lengaigne et al., 2007). This may be appropriate for the majority of the open ocean, but will underestimate chlorophyll concentration throughout this domain. This also neglects additional impact of suspended sediment. The scheme tested by (O'Dea et al., 2017) uses ~~of~~ a single-band light attenuation scheme, where the depth of penetration varies with the depth of bathymetry. While this scheme may be appropriate for regions of the North Sea where depth is likely proportional to the water clarity, it does not account for high chlorophyll concentrations in deeper, nutrient-rich waters, such as the Norwegian Trench, and the North East Atlantic. A test has been run using this scheme in the AMM15 domain (not shown). Some improvement is seen in the North Sea, however other regions see increased biases emerge in the summer. A cold surface bias results off-shelf, and SST is also further reduced in the Norwegian Trench, where a cool bias already exists in the summer. Further tests are needed to investigate the impact of including 2D chlorophyll variability, or KD-490 schemes.

The Norwegian Trench shows increased anomalies in AMM15 compared with AMM7 (Region 3, Figure 6k,l). In addition to the fresh anomaly found at the surface (Figure 4), there is also a warm, saline anomaly at depth. These anomalies suggest a potential difference in the balance of heat and freshwater transport between the Atlantic and Baltic Sea through the Trench. Given that both the ~~Baltic and Atlantic~~ Atlantic and Baltic boundaries have been altered in this configuration, the impact of such changes on the Norwegian Trench transport should be the subject of further study. While the addition of barotropic forcing at the Baltic boundary should lead to improvements in AMM15, $1.5\,\mathrm{km}$ resolution is still relatively coarse when compared to narrow channels within the Danish Straits. It is also possible that the difference in SSH forcing used at the Atlantic and

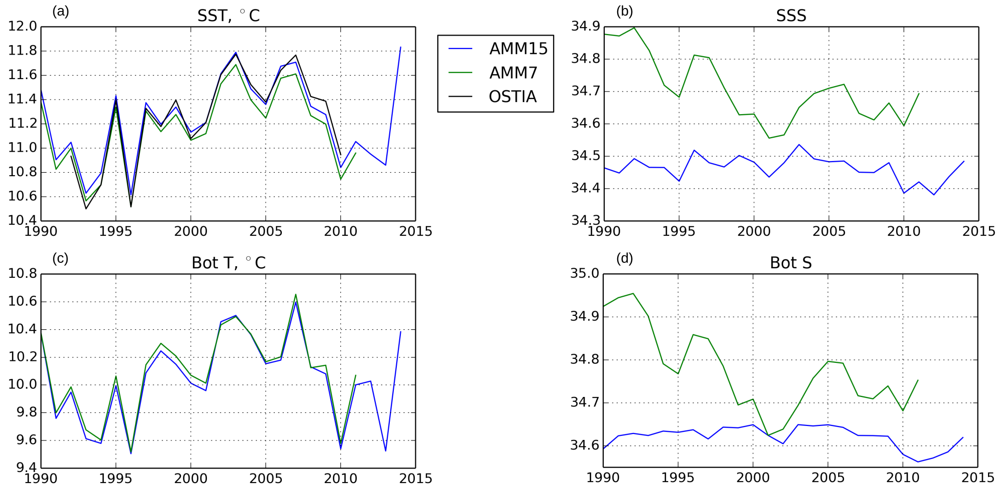

Figure 8. Annual mean temperature (left) and salinity (right) for the surface (top) and bottom (bottom) over the continental shelf (shaded region shown in Figure 6). Blue and green lines show mean values for AMM15 and AMM7, respectively. For SST (top left), OSTIA CCI reanalysis (Merchant et al., 2014) are provided for comparison.

Baltic boundaries could lead to an inaccurate flow through the region (e.g., Mattsson, 1996). Further work is needed to assess whether the anomalies seen in AMM15 result from limitations in the model grid and bathymetry, or forcing at either the Baltic or Atlantic boundaries.

3.4 Temporal Variability

Both AMM7 and previous configurations have been used for long term climate studies, as well as operational forecasts. Aside from being able to reproduce a mean climatology, it's then also crucial to assess whether model simulations are stable, and can reproduce observed variability in the region. Figure 8 shows the temperature and salinity variability over the shelf during the course of the simulation. For both the models shown here, the surface temperature trends agree with OSTIA data, with an increase through the 1990s reaching a maximum in the mid 2000s, followed by cooling in 2010. Previous studies have shown a warming trend since the 1980s across the NW Shelf, with an average increase in SST of between 0.1 and $0.5^{\circ}\mathrm{C\,decade}^{-1}$ over the period 1983-2012 (Dye et al., 2013a). This warming has been mostly attributed to atmospheric temperatures (e.g., Meyer et al., 2011; Holt et al., 2012).

Across the shelf, both models show the same variability, consistent with the fact that both are forced with the same atmospheric data (ERA-Interim). However, the mean surface temperature in AMM15 has a reduced bias compared with AMM7. Analysis of the monthly timeseries (not shown) shows that the difference between the two models is greatest in spring, when AMM7 has a larger cool bias across the shelf (also shown in Figure 3). Breaking the variability down into subregions of the shelf, again both model show similar variability (not shown), with any remaining bias matching that shown in the mean climatology.

Observations from bottom trawl surveys within the North Sea suggest that bottom temperatures have similarly increased, by $\sim 0.2-0.5^{\circ}\mathrm{C\,decade}^{-1}$ during 1983-2012 (Dye et al., 2013a). Figure 8 shows the average bottom temperature across the shelf for both AMM15 and AMM7. Both models show similar variability to the surface temperature, increasing from the mid 1990s to a maximum mean temperature in 2007, followed by a decrease in 2010.

It may be expected that the SSS or sub-surface salinity may show greater differences between the models. Temperature on the shelf is predominantly influenced by surface heat fluxes. While salinity will be partly influenced by evaporation (and hence temperature), it will also be significantly influenced by local river runoff and advection (both of which will differ between the models). Comparing the two models, there is an obvious decreasing trend in AMM7, compared with no significant trend for AMM15 (Figure 8). Similar trends are again found in both the surface and bottom of the water column.

~~The stability shown in AMM15 is reassuring, suggesting that the model is in a relatively stable state. It is unclear what may cause the drift seen in AMM7, however this may be related to the boundary forcing (which differs to that used in AMM15).~~ For salinity, there are no shelf-wide timeseries for comparison. However, previous studies have analysed trends in the UK coastal waters (Dye et al., 2013b). Bottom trawl observations suggest a positive trend in the North Sea, from 1971-2012, likely due to the influence from inflowing Atlantic water (Hughes et al., 2012). However, in other regions, there is no significant long-term trend, with large ranges of sub-decadal variability influenced by river runoff around the coast and southern North Sea. While we can't say for certain, the stability shown in AMM15 may then be reassuring, suggesting that the model is in a relatively stable state. It is unclear what may cause the freshening seen in AMM7. However, this may be related to the different boundary conditions and initialisation. Both models are initialised and forced with free-running simulations prior to 1990. As AMM7 appears to drift towards the AMM15 mean value, this suggests there may be a larger difference between consecutive forcing sets for AMM7. The trend here may then be an adjustment of towards the state of the GLOSEA ocean.

4 Discussions and Future Work

The next generation ocean forecast model for the European NWS has been introduced here, with the intention that it will become operational in 2018. The new configuration has increased resolution, with 1.5 km grid spacing throughout the domain, compared to ~ 7 km in the previous configuration. A 30 year non-assimilative run has been used to demonstrate the ability of this new configuration (AMM15) to represent the mean state and variability of the region, in comparison with the the current operational system (AMM7).

~~While there is still uncertainty surrounding the absolute causes, it is clear~~ The increased resolution does make this model more expensive to run. However, the capacity is there to provide this new system, and with increased resolution there is greater potential for added value to end users. The full operational system will use different boundary conditions and include data assimilation. Therefore, it is not possible to say for certain how the skill of operational forecasts will compare with the existing system. However, this study provides insight into how the physics-only configuration performs, and where we should expect to see improvements compared to the existing 7 km domain. While some biases are common between the two models, there is an overall improvement in mean climate across the North West Shelf, and there is plenty of scope for further improvement.

Tidal signal within a regional model configuration is to a large extent determined by the boundary conditions and bathymetry. AMM15 and AMM7 have both different bathymetry and tidal forcing at the open boundary. Given this significant change in configuration, it is then reassuring to see that AMM15 ~~provides a comparable if not improved representation of conditions across the majority of~~ continues to provide a reasonable representation of the ~~North West Shelf region.~~ major tidal constituents. The minimum depth within the model remains a limiting factor here, so future improvements will focus on the addition of wetting and drying within the domain, which is currently in development for NEMO vn4.0.

Similar biases remain ~~on~~ for stratification across the continental shelf, particularly in the North Sea. Given the fact that climate on the shelf can be predominantly driven by a balance of vertical forces (surface buoyancy fluxes and vertical mixing) rather than horizontal advection, it is not surprising that the two models are similar. Both have the same atmospheric forcing, vertical mixing schemes and vertical resolution.

For regions that show little or no improvement, this provides motivation for targeted bias reduction. In the North Sea, there is a need for improved understanding of stratification variability, and how this is represented across the shelf. Bias reduction here will initially focus on improvements to the light attenuation and vertical mixing parameterisation schemes. These schemes should lead to improved stratification and surface climatology across the whole domain, and will be the focus of future study.

There has been substantial progress in developing mixing models in shelf seas over recent decades (e.g. Umlauf and Burchard, 2005), however they still struggle through a lack of specific physical process representation (Luneva et al., 2017). Bringing together recent developments in direct observations of turbulent properties and LES modelling, for example in research projects such as PycnMix (Pycnocline Mixing in shelf seas) and OSMOSIS (Ocean Surface Mixing , Ocean Sub-mesoscale Interaction Study) (Belcher et al., 2012), has the potential to lead to substantial improvements in vertical mixing schemes for the shelf seas.

Further work is also needed to assess currents and transport within the region, ~~and its~~ along with their impact on model hydrography. In the Norwegian Trench, biases are found to be larger than the current operational system. Heat and freshwater transport through the Trench will be influenced by both the Baltic and Atlantic boundaries. Given the number of factors which are likely to impact on changes seen here (including both the location and data used for boundary forcing), further experiments are needed to assess the response to individual perturbations. In particular, significant changes have been made to the Baltic boundary, which warrant further investigation. Attribution of biases to changes in the location of boundaries, chosen forcing products, or local heat or freshwater fluxes within the region, could then inform future development of the operational system.

This model has been developed with operational implementation as the primary goal. However, aside from this purpose, this configuration also provides an excellent new tool for research. This study has focused on the long term climatology and stability of the model, but there are many differences to be seen on shorter timescales, and smaller spatial scales (e.g., Guihou et al., 2017; Badin et al., 2009; Holt and Proctor, 2008). As with the Norwegian Trench, further research is needed to attribute improvements in the model climatology across the region to changes in horizontal resolution as opposed to boundary locations, forcing or parameterisation schemes. ~~There~~ With the increased resolution allowing for improved representation of mesoscale to submesoscale processes across the domain (such as eddies, fronts and internal tides), there is a wide scope for process studies here. The impact of such processes on forecast skill, will also be the subject of further study.

Table 2. Compilation keys for AMM15 simulations.

Key	Description
`key_bdy`	Use open lateral boundaries
`key_dynspg_ts`	Free surface volume with time splitting
`key_ldfslp`	Rotation of lateral mixing tensor
`key_tide`	Activate tidal potential forcing
`key_vvl`	Variable Volume Layer
`key_zdfgls`	Generic Length Scale turbulence scheme
`key_harm_ana`	Restartable tidal analysis
`key_shelf`	Diagnostic switch for output
`key_iomput`	Input output manager
`key_nosignedzero`	Ensure reproducibility with SIGN function
`key_vectopt_loop`	Vector optimisation

One of the biggest challenges ahead will be to see how the high resolution simulation responds to data assimilation and coupling with biogeochemistry, as part of the operational system. However, this configuration has already been implemented as the ocean component of the UK Environmental Prediction (UKEP) system (Lewis et al., 2017), where it has been coupled with atmospheric and wave models. Initial results are very promising, and demonstrate the value of increased ocean resolution for simulating the wider climate system.

5 Code availability

AMM15 is a regional configuration of NEMO (Nucleus for European Models of the Ocean), at version 3.6 stable (Madec, 2016). Model code is freely available from the NEMO website (www.nemo-ocean.eu). After registration the FORTRAN code is readily available using the open source subversion software (http://subervsion.apache.org). Additional modifications to the NEMO v3.6 trunk are required for AMM15 simulations, and these changes can be found in the NEMO repository. The simulations discussed here were compiled at NEMO r5549. However, the original changes have now been merged under r6232, and can be found within the following branch: `branches/UKMO/AMM15_v3_6_STABLE_package`. Tests have confirmed that there is no significant difference in model results between these two code revisions.

The compilation keys required for these simulations are listed in Table 2.

An example namelist for the control simulation, containing all chosen parameterisations, can be found under the following DOI: 10.13140/RG.2.2.27237.40164 (Graham, 2017).

6 Data availability

The nature of the 4D data generated requires a large tape storage facility. The data that comprise the AMM15 hindcast simulation are of the order of 90TB. However, the data can be made available upon contacting the authors.

Bathymetry was obtained from the EMODnet Portal: EMODnet Bathymetry Consortium, EMODnet Digital Bathymetry (DTM), EMODnet Bathymetry (September 2015 release).

River gauge data was provided by pers. comm from Dr. S. M. van Leeuwen, CEFAS, Lowestoft, UK. The riverine forcing used for this control simulation can be made available upon request.

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