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An analysis of the impact of Ocean Gliders on the AMM15 model.

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1 Plain language summary

The Atlantic Margin Model (AMM15) is one of the ocean models used by the Met Office, predicting ocean circulation in the North Atlantic approaches and shelf seas around the UK at a resolution of 1.5km. Model analyses and forecasts are used in a wide range of applications including search and rescue, oil spill response and providing sea-surface temperature boundary conditions for Met Office numerical weather prediction.

The majority of observations used to constrain the AMM15 model are surface measurements collected by satellites. In situ and sub-surface observations of shelf seas around the UK are relatively sparse, for example because the North Sea's limited area and the density of infrastructure means that the drifting surface buoys and Argo profiling floats we use for measuring the open ocean are unsuitable.

In this environment, ocean gliders are the ideal observation instrument. Their ability to propel and steer themselves allows them to avoid infrastructure and to provide observations from a chosen area and depths.

For this experiment, ocean gliders were deployed near the Shetland Isles and their observations were inserted into a trial AMM15 model. This trial was compared to a control AMM15 model (without glider data) and the differences between the two were studied.

We observed that the gliders had a greater impact on the AMM15 model than anticipated, but their data overall increased the trial model's accuracy. Glider data are now regularly assimilated into the operational AMM15 model.

2 Introduction

The Atlantic Margin Model running at a 1.5km resolution (AMM15) is an ocean model employed by the Met Office to provide 6-day forecasts for the European North-West Shelf Seas around the UK.

A key requirement for AMM15 is for it to provide accurate Sea Surface Temperature (SST) forecasts since its temperature data are used as boundary conditions for the high resolution UK atmospheric model (UKV) (Tonani et al. 2019). AMM15 therefore has the same domain as UKV and any changes to AMM15 will consequently have wider implications for the Met Office's forecast products. A bathymetry map of the AMM15 domain is provided in **Figure 1**.

AMM15 includes a data assimilation system, the purpose of which is to process observations and combine them with a short-term forecast model field. This is then used during the forecasting calculations to constrain the model fields towards the observations, helping to ensure that the forecasts are accurate (Tonani et al. 2019; King et al. 2018). Hence, data assimilation is a dynamic process which updates each model run. Data assimilation also compensates for the fact that the scale of ocean features varies spatially, as the deep ocean will have larger features compared to smaller, shallower seas, which is an important consideration for the AMM15 model since its domain includes deep and shallow seas.

The majority of observations used in the AMM15 model are surface measurements of temperature and sea-surface height collected by satellites (**Table 1**). In situ observations are very sparse in the shelf seas around the UK as the limited area, variations in depth and density of infrastructure (particularly in the North Sea) makes use of drifting surface buoys and profiling floats unsuitable. Argo floats, which are our main means of profile data collection (Wong et al. 2020) are designed to operate in the wider ocean and dive to deep depths to carry out their mission, which makes them inappropriate for such shallow waters.

Table 1: Observation datasets used in operational AMM15 model.

Instrument	Observation Type
Insitu	SST and temperature/salinity profiles from: Drifter and moored buoys. Ocean Gliders. Argo floats. XBT and CTD instruments. Ships and Ferry boxes. (Tonani et al. 2019)
SEVIRI	Satellite Sea Surface Temperature
MetOp	
AMSR2	
VIIRSG	
SLSTR	
CryroSat	Satellite Sea Level Altimetry (SLA)
AltiKa	
Jason3	
Sentinel 3 A and B SRAL	
Sentinel 6 POSEIDON-4	

XBT=Expendable Bathythermograph. CTD=Conductivity Temperature Depth. Ferry boxes=Instrument packages carried by commercial ferries.

In this environment, ocean gliders are the ideal instrument. Their ability to propel and steer themselves allows them to avoid infrastructure and to provide observations from a chosen area and depths. A project in partnership with the National Oceanography Centre (NOC) was initiated, where NOC deployed ocean gliders near the Shetland Isles. This report covers a period of 5 months. Two gliders were initially operating. These were replaced by a single glider later in the period. The data from these were assimilated into the AMM15 model and their impact measured.

In section **3**, the background oceanography of the North Sea is briefly summarised. Section **4** describes the experiment methodology; the results and conclusion are presented in sections **5** and **6** respectively.

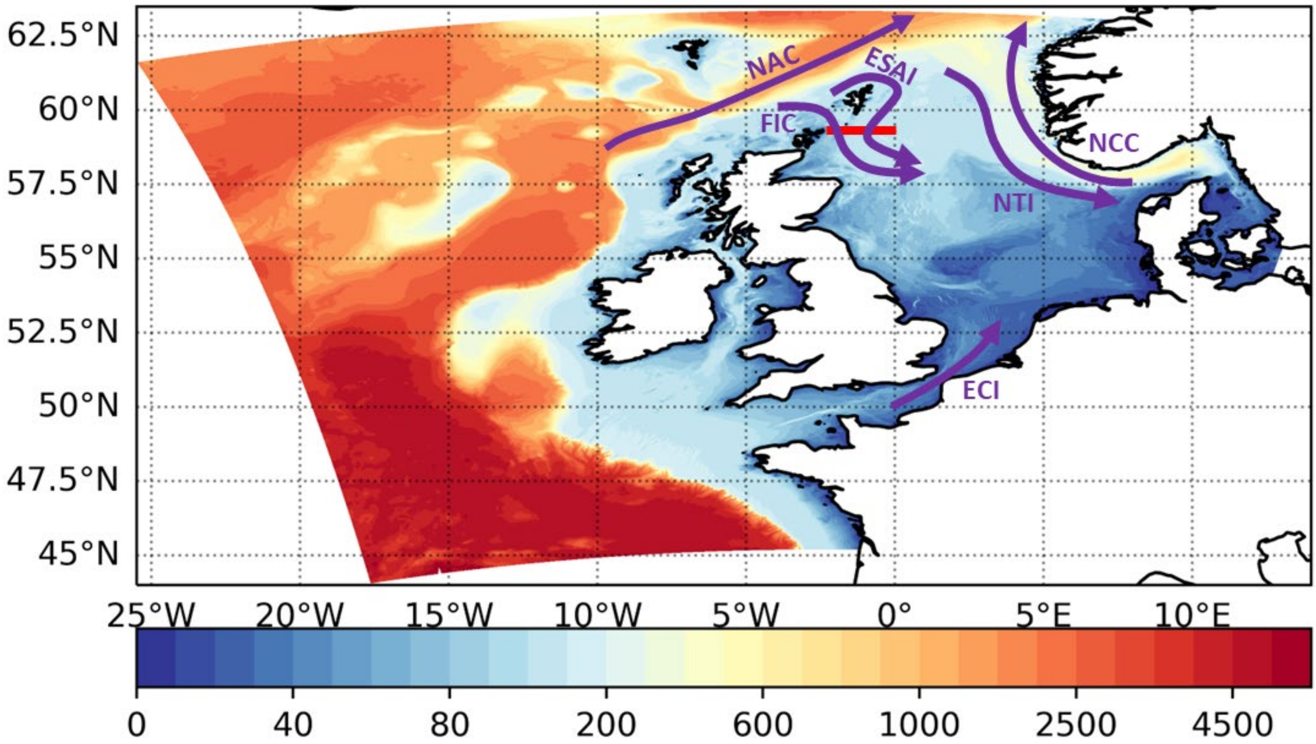

Figure 1: Bathymetry map of the AMM15 domain with main currents and JONSIS line (red) overlaid. ***Note the non-linear colour scale.*** *Current names: North Atlantic Current (NAC), Norwegian Trench Inflow (NTI), Norwegian Coastal Current (NCC), Fair Isle Current (FIC), East Shetland Atlantic Inflow (ESAI), English Channel Inflow (ECI).*

Plot based on plotting code produced for the King and Martin (2021) paper. Currents from Sheehan et al. (2017) and Turrell et al. (1996)

3 Background oceanography

A shelf sea is a coastal sea formed by a section of the continental shelf which protrudes into the ocean. The North Sea is an example of a shelf sea and it is mostly shallow (mostly 20-150m deep) with the exception of the Norwegian Trench, a submarine feature off the Norwegian Coast where depths exceed 700m at the Skagerrak end (the passage between Norway and Denmark) (Vindenes et al. 2018).

There are several currents relevant to this study labelled in **Figure 1**. Oceanic waters that feed into the North Sea basin from the North are supplied by the North Atlantic Current (NAC). The Norwegian Trench Inflow (NTI) is a deep-water current which moves along the west edge of the Norwegian Trench and is the largest in term of volume transport. When it meets brackish water from the Baltic at Skagerrak, the NTI retroflects and flows northwards along the surface as the Norwegian Coastal Current (NCC) (Winther and Johannessen 2006).

The two Shetland Isles currents, the Fair Isle Current (FIC) and the East Shetland Atlantic Inflow (ESAI) (**Figure 1**) are surface currents with a combined inflow similar to the NTI (Winther and Johannessen 2006). They eventually merge into the Dooley current (not pictured) which travels to Skagerrak to join the NCC and flow out of the North Sea basin. (Sheehan et al. 2017; Winther and Johannessen 2006; Vindenes et al. 2018). The English Channel Inflow (ECI) is weak compared to the northern inflows and is included in **Figure 1** for the sake of completeness.

Due to the fact that the majority of the NTI water mass is transported out via the NCC, the FIC and ESAI currents are therefore the main contributors to water entering the North Sea (Sheehan et al. 2017). To allow more consistent surveys of this important region, ocean researchers have assigned near the Shetland Isles a 127km-long Joint North Sea Information System (JONSIS) line at a latitude of 59.28°N and running from longitudes 2.23°W to 0° (**Figure 1** - red line). The JONSIS line crosses the Shetland currents and is surveyed multiple times a year by Scottish and Norwegian research ships (Sheehan et al. 2017).

4 Experiment Methodology

Initially, two ocean gliders (Ammonite and Cabot) were deployed near the Shetland Isles to study the ocean along the JONSIS line on 1st September, and the Met Office observations database (MetDB) started receiving data from them on 5th September. These gliders were later recovered and replaced with the glider Coprolite on 5th December (**Figure 2**). The Coprolite dataset has a gap from 20th December to 5th January.

The AMM15 model produces a 6-day forecast which runs at 5:15am each day, and each forecast is initialised using observations data for the two days prior to 0000 UTC on the run date. Therefore, a glider data point collected that day must arrive in the MetDB before 5:15am in two days' time if it is to be included in any of the model runs.

Apart from the dataset gaps mentioned earlier, the glider data have been arriving in time for use in the AMM15 systems over 90% of the time.

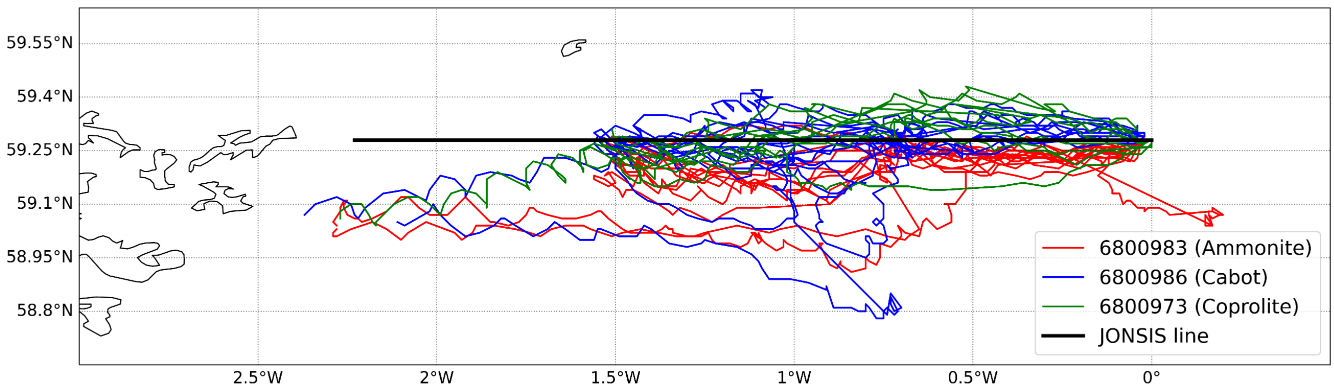

Figure 2: Location of gliders between 01/09/2022 to 25/01/2023

Two versions of the AMM15 system were run in parallel, one where the gliders were extracted from the MetDB and assimilated into the experiment. The control was identical except that the glider data were extracted in do-not-assimilate mode, ensuring that the glider data were incorporated into the system but were not used (**Figure 3**). It can be seen that the data points in the control (**Figure 3 - left**) are marked as bad because they are not assimilated, rather than being rejected by quality control. The experiment was run from 1st

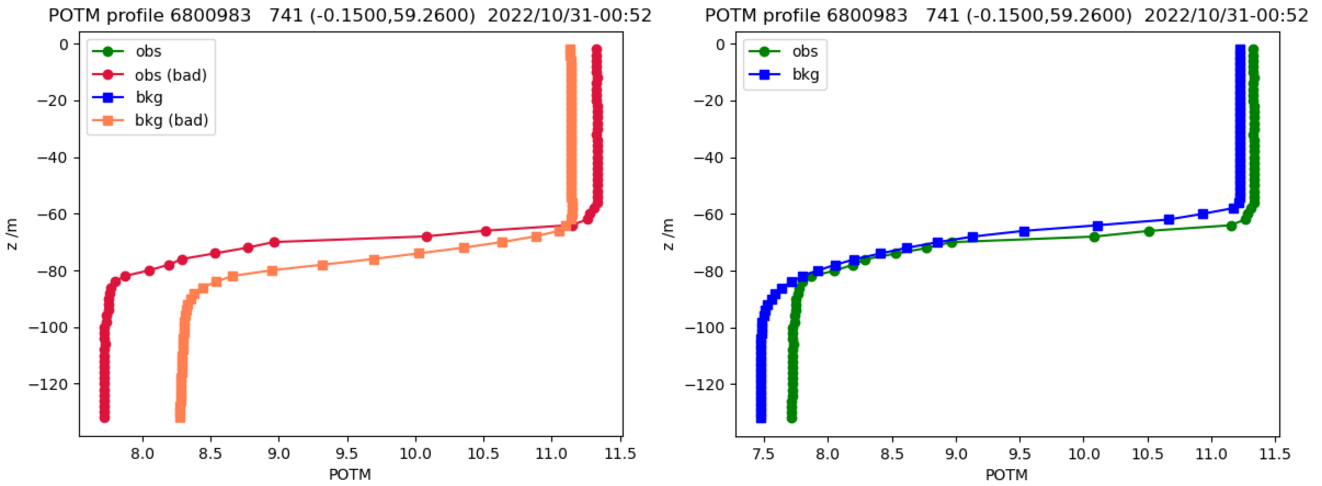

Figure 3: Data assimilation treatment example. Control (left). Experiment (right)

September 2022 to January 25th 2023.

5 Results

The AMM15 system produces temperature, salinity and current speed fields for a range of depths (0 to 5610 metres), while the Sea Surface Heights (SSHs) are produced for the surface only. The gliders measure temperature and salinity values, and therefore it is in these model fields that we expect to see the largest changes.

AMM15 generates daily average analyses and forecasts from -36 hours to +132 hours relative to the cycle time at 24 hour intervals. The -36 and -12 hour “forecasts” are actually two forecast initialisation analyses which allow AMM15 to assimilate all available observations before generating the +12 to +132 hour forecasts (Tonani et al. 2019). Therefore, the AMM15 -36 hour initialisation analysis should represent the most accurate realisation of the North Sea. Although all model analysis and forecast days were examined in the investigation, in the interest of conciseness, this report will present the results obtained from the -36 analysis and +132 hours forecast.

5.1 Field plot investigations

The first part of the investigation was to compare the AMM15 model fields generated by the experiment and control systems. Four different fields were studied:

- Bottom temperature
- Surface temperature
- Surface salinity
- Sea Surface Height

The AMM15 model files do not contain a bottom salinity product, and therefore it is not investigated in this report.

For each of the daily model fields, the control was subtracted from the experiment. Videos are the best method of visualising the changes over time and are available with open access on Zenodo (see Appendix in **Section 7**).

To determine whether the experiment minus control differences were persistent or merely transient, a second investigation was carried out where the fields generated by each system were averaged over time before being subtracted. Three sets of plots were produced for different averaging time periods; the entire experiment run (1st September to 25th January), for each month and for each week, and all are available on Zenodo (see Appendix in **Section 7).**

In this report, the monthly average difference plots are displayed, and a summary of their behaviour is outlined below:

Bottom temperature (**Figure 4**):

The behaviour of the models in the JONSIS line region and in the wider domain (the area outside the JONSIS region) can be quite different, so we will examine these regions separately.

JONSIS line region: The experiment fields in the region of the JONSIS line are initially colder before converging towards the control in January 2023. The Norwegian Trench Inflow (NTI) appears to be colder, whereas the temperatures within the Norwegian Trench itself are warmer.

Wider domain: Locations where the Atlantic Ocean floor meets shallower waters (such as at the shelf sea boundary) (**Figure 1**) show increased variability but no clear preference for warmer or colder values.

Surface temperature (**Figure 5**):

JONSIS line region: For the -36 model fields, although the experiment is initially colder at the beginning, it becomes very mixed and turbulent throughout the period with no clear trend towards warmer or colder values. In the +132 fields the experiment is more consistently slightly colder than the control before converging towards the control in January 2023 (in common with the bottom temperature).

Wider domain: What is interesting is that the glider data has the least impact in the glider region, but a strong impact elsewhere.

An important point to note is that the vast majority of SST observations used in the AMM15 model come from satellites and these measurements will therefore dominate over any SSTs observed by gliders.

One explanation for the observed patterns is that the gliders are not changing the absolute SST values, but rather that small differences have caused a shifting of the currents and eddies, resulting in there being greater differences further away from the glider region.

Surface salinity (**Figure 6**):

JONSIS line region: Throughout the time period, the experiment is consistently and significantly saltier than the control in the glider region. The Norwegian Coastal Current (NCC) displays more variability.

Wider domain: The experiment displays a consistent freshening off the West Coast of Ireland which interestingly mirrors the shape of the sea floor (**Figure 1**). The reason behind this is unknown and warrants further investigation.

Sea surface height (**Figure 7):**

JONSIS line region: The experiment is consistently lower than the control throughout the timeseries.

Wider domain: The SSH values are generally very mixed throughout the region, except in the Southwest edge of the AMM15 domain where there is a point where the SSH is intermittently but consistently extremely low. This is more obvious when viewing the daily animation video (see Section 7).

As part of the AMM15 data assimilation process, temperature and salinity increments are used to calculate the density increments, which in turn is used to calculate the SSH values (Weaver et al. 2006).

It can be seen from **Figure 4** to **Figure 6** that the gliders are adding negative temperature and positive salinity changes in the glider region; both these changes will lead to an increase in the density and therefore a lower SSH.

The persistence of the SSH changes suggests that they are not conflicting with any satellite Sea Level Altimetry (SLA) anomalies that are being assimilated (which indicates that these AMM15 model changes are representative of the observations).

Overall observations:

It was expected that the glider data would primarily affect outputs in the Northern North Sea, but as can be seen, their impact propagated across the entire AMM15 domain.

As detailed in section 2, the AMM15 data assimilation process uses a combination of observation and previous model fields to constrain the forecast. The Off-shelf region is dominated by deep water eddy structures which are more random in nature and so are difficult for the data assimilation to constrain. Therefore, small perturbations will lead to larger differences in this region. The On-shelf region is dominated by tides and currents which are smoother and more predictable, which would lead to a more stable forecast field. In this region, the gliders would likely produce more consistent effects.

One common feature in all the variables examined, is that there are very few changes in the Southern North Sea basin. One proposed theory is that the Dooley Current is limiting the penetration of the impact to the Northern and central parts of the North Sea basin, although this may simply reflect the lengthscales over which an observation will affect the wider model domain as specified in the data assimilation scheme.

Research has shown that the JONSIS region of the North Sea exhibits seasonal stratification: typically it is thermally stratified in the Spring and remains so until Autumn processes remix the water column until it transitions to continuously mixed conditions during the Winter (van Leeuwen et al. 2015). The same research also showed that the Norwegian Trench region is permanently stratified.

This seasonal stratification would partially explain the diminishing experiment-control differences with sea bottom temperatures in the JONSIS region. In the scenario where the control AMM15 were stratified and too warm in September, this would become less of an issue as the overall sea-temperature cools and becomes more well mixed into the winter. Therefore, the control would start to converge with the experiment, as can be observed in the bottom temperature plots (**Figure 4**).

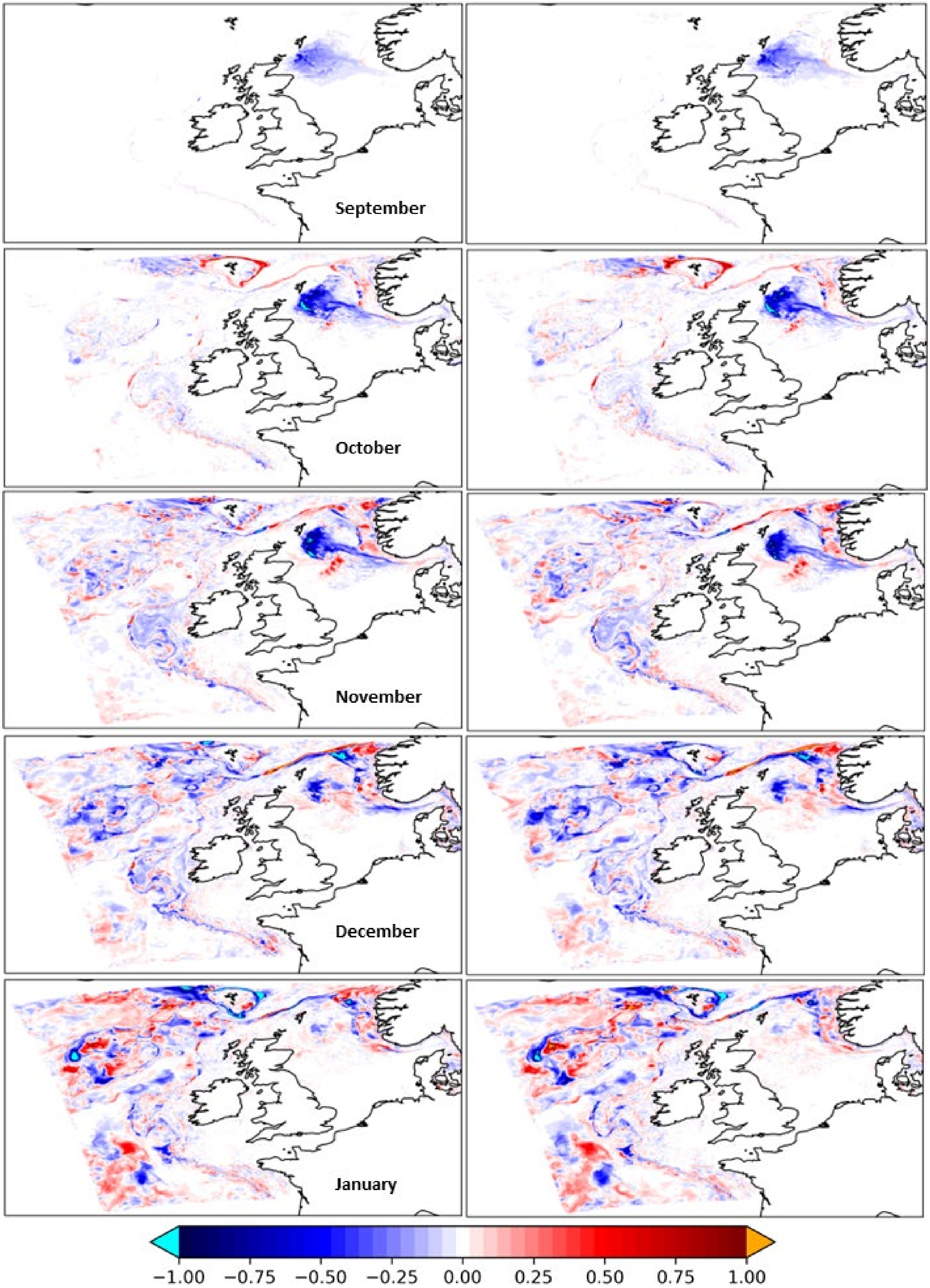

Figure 4: Bottom temperature experiment-control difference monthly average fields. Left – values from -36 model run. Right: values from +132 model run

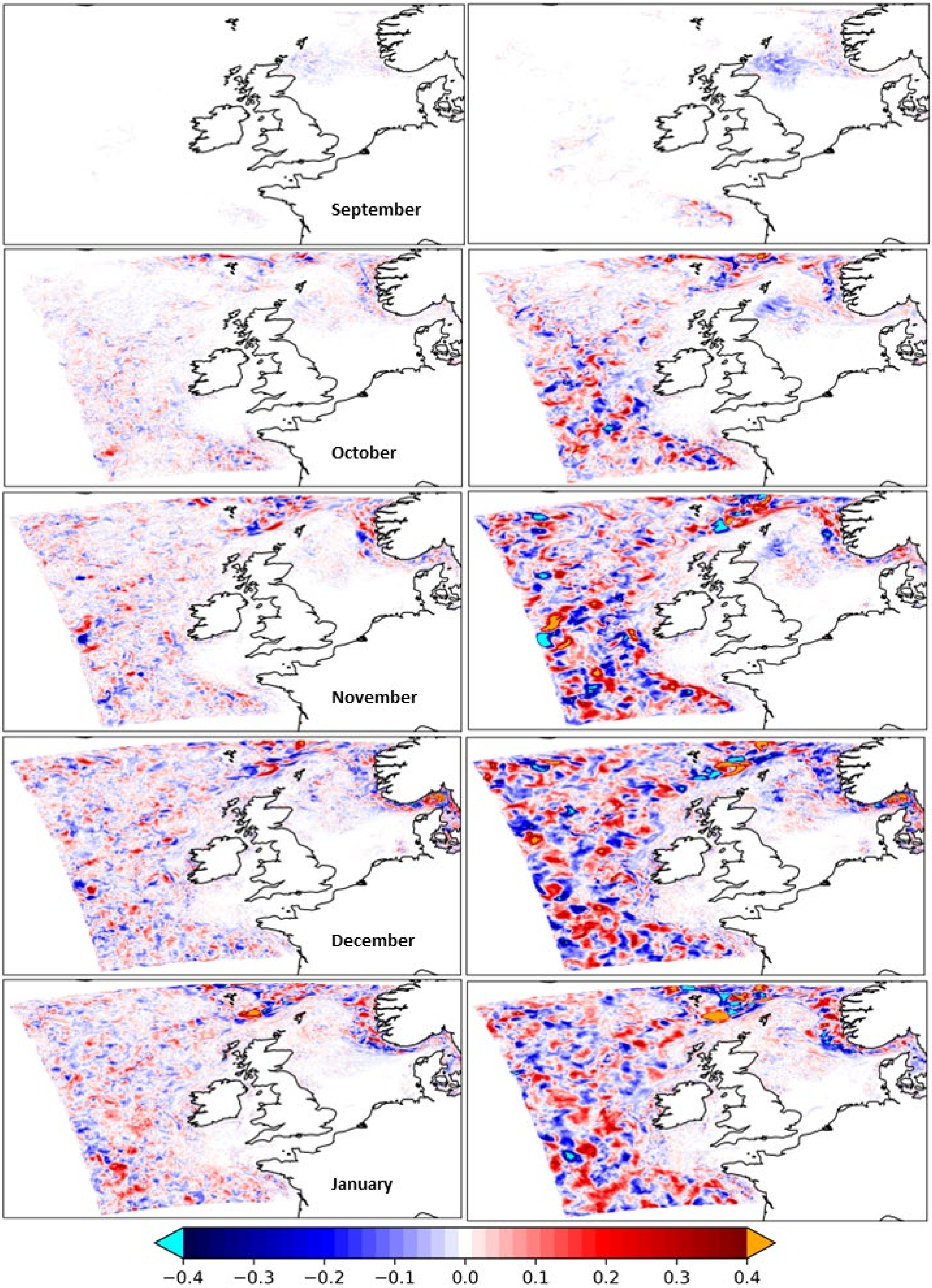

Figure 5: Surface temperature experiment-control difference monthly average fields. Left – values from -36 model run. Right: values from +132 model run

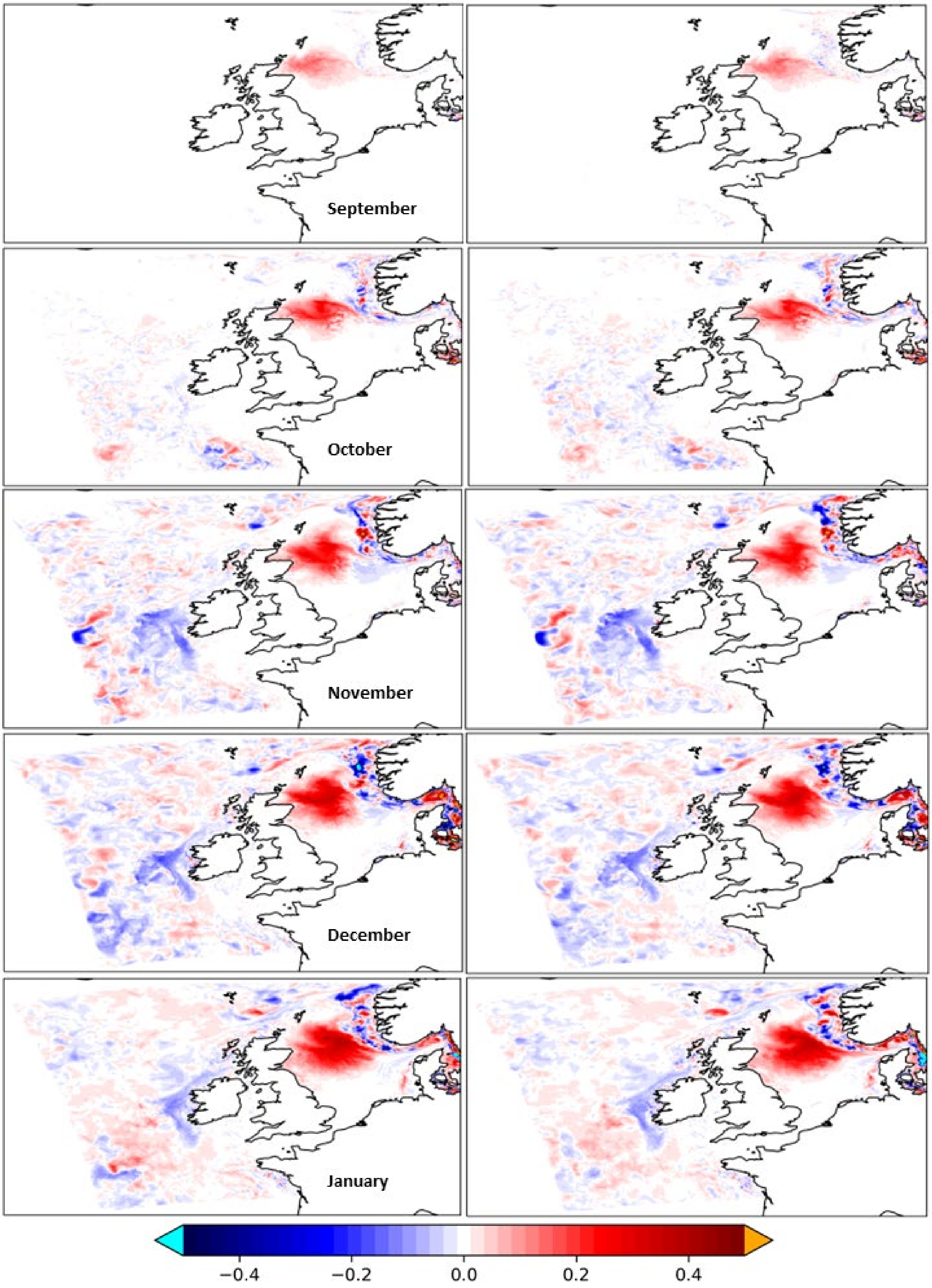

Figure 6: Surface salinity experiment-control difference monthly average fields. Left – values from -36 model run. Right: values from +132 model run

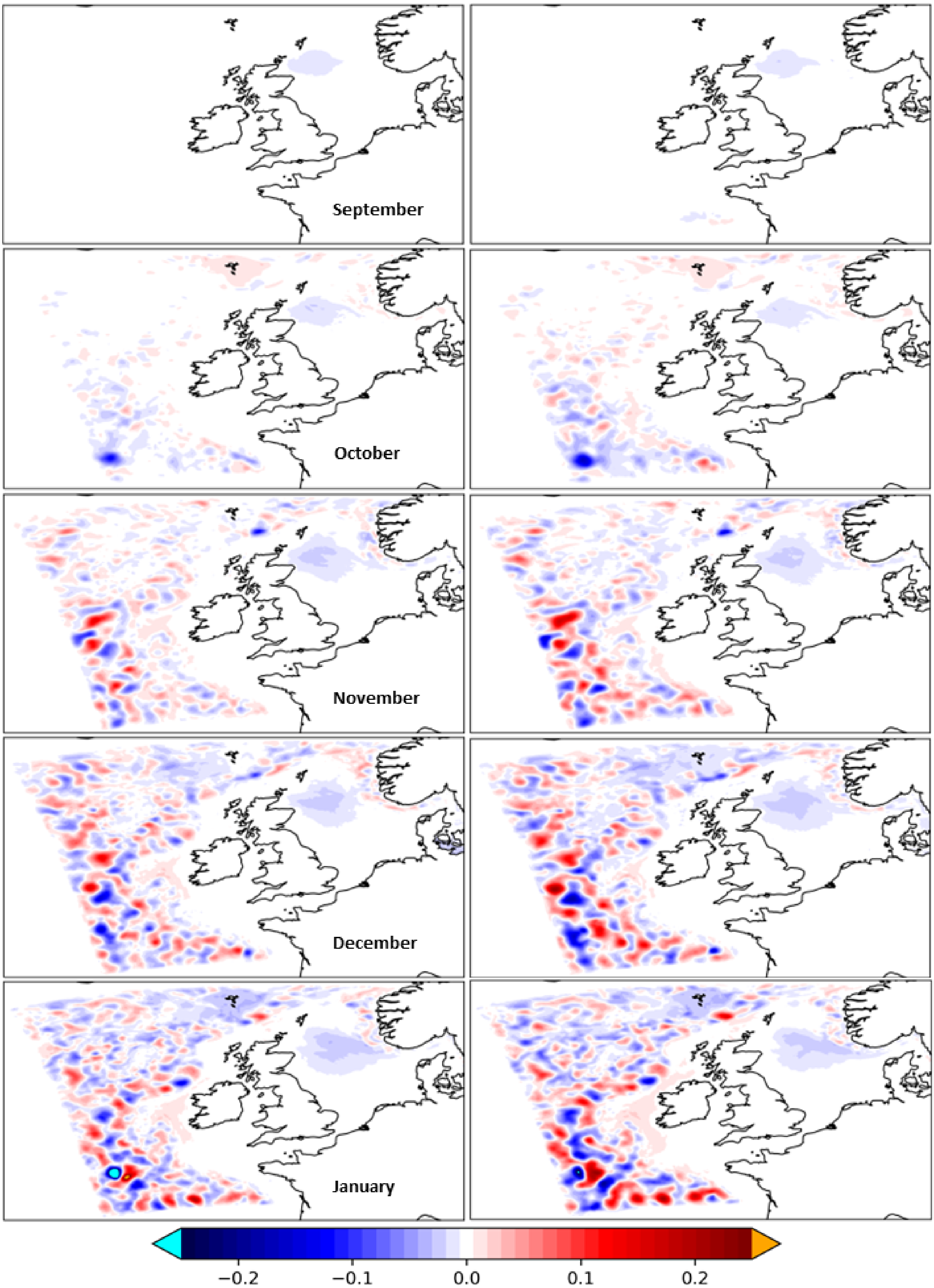

Figure 7: Sea Surface Height experiment-control difference monthly average fields. Left – values from -36 model run. Right: values from +132 model run

5.2 Using the Obsstats software package for validation

To assist with the validation of ocean models, the Ocean Team developed the Obsstats software package, which is capable of comparing different models and their behaviour over time for fourteen different regions.

Obsstats uses the observations as assimilated by the AMM15 model minus the background field (which is the calculated model field equivalent to each observation) and these are extracted from the nearest simulation timestep.

These observations minus background (omb) fields are then binned (either spatially or temporally depending on the statistic required) and used by the Obsstats software for its calculations. Bear in mind that, consequently, a location within a bin or region with dense observations will have a greater impact on the statistics.

For this investigation, we are concerned with just four regions, the first being the entire AMM15 domain, the other three are outlined by the regional masks shown in **Figure 8**. Note that the North Sea mask does not include the Norwegian Trench region.

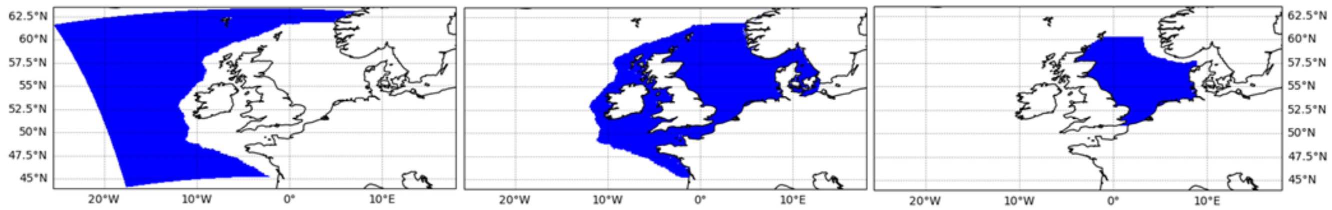

Figure 8: Masks used in Obsstats study. Blue is the included area. Left: Off shelf region, Middle: On shelf region, Right: North Sea

We are focusing on these four regions because the Sea Surface Temperature (SST) timeseries results from the Obsstats in-situ validation showed that the two models produced virtually identical outputs for other regions of the AMM15 domain.

The SST results from these four regions are displayed in **Figure 9** which shows the omb statistics for each model over time. Time series plots were also generated for sea level anomaly fields (**Figure 10**).

For both datasets it can be seen that, while there are differences, they are extremely small. This is unsurprising given that the primary impact on the SST and SLA fields is from satellite observations, due to the larger volume of data available. They also lend weight to the theory that the variability observed in the model fields in the off-shelf region (**Figure 4** to **Figure 7**) is not detrimental to the model performance.

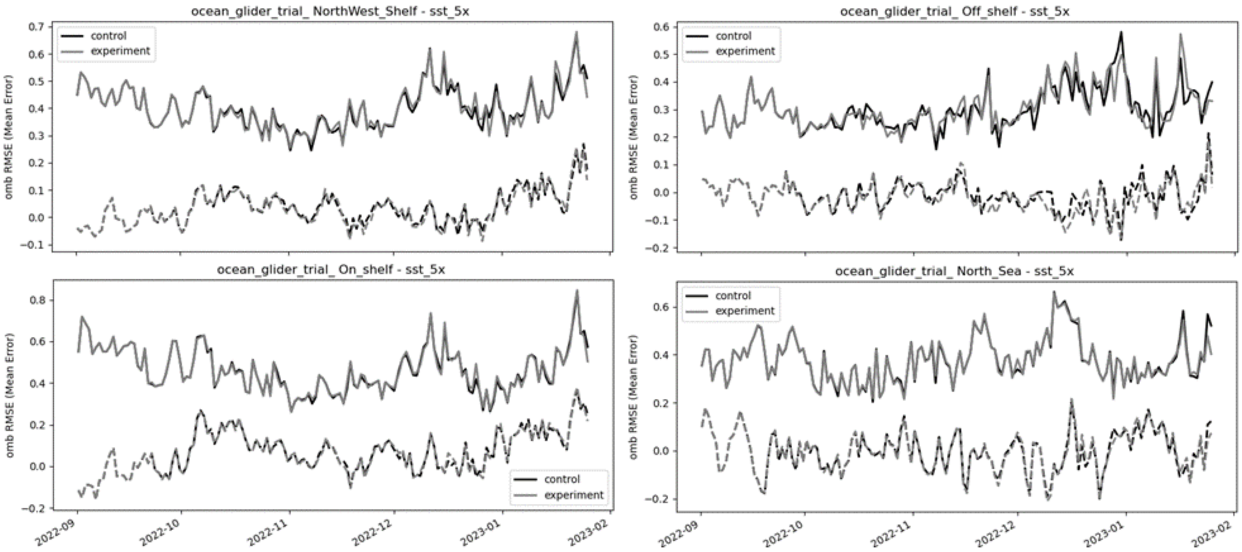

Figure 9: Timeseries of mean and root mean square (RMSE) omb differences for SST. Solid line = RMSE. Dashed line = Mean Error*: Whole AMM15 domain (top left), Off shelf (top right), On shelf (bottom left) and North Sea (bottom right).*

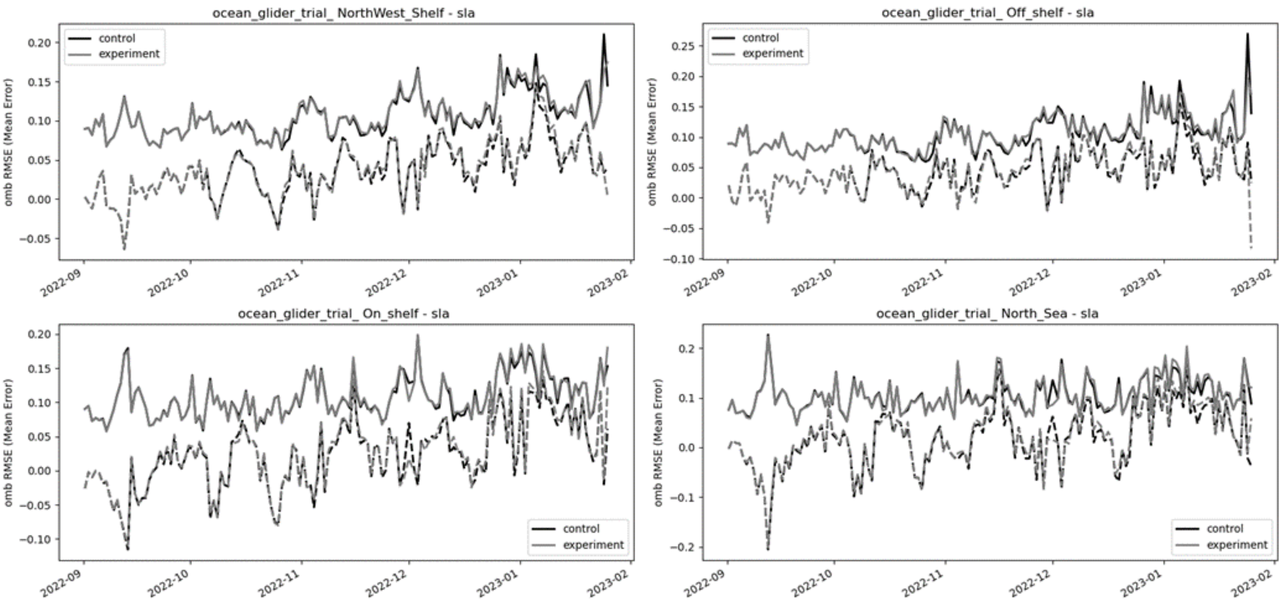

Figure 10: Timeseries of mean and root mean square (RMSE) omb differences for Sea level altimetry. Solid line = RMSE. Dashed line = Mean Error*: Whole AMM15 domain (top left), Off shelf (top right), On shelf (bottom left) and North Sea (bottom right).*

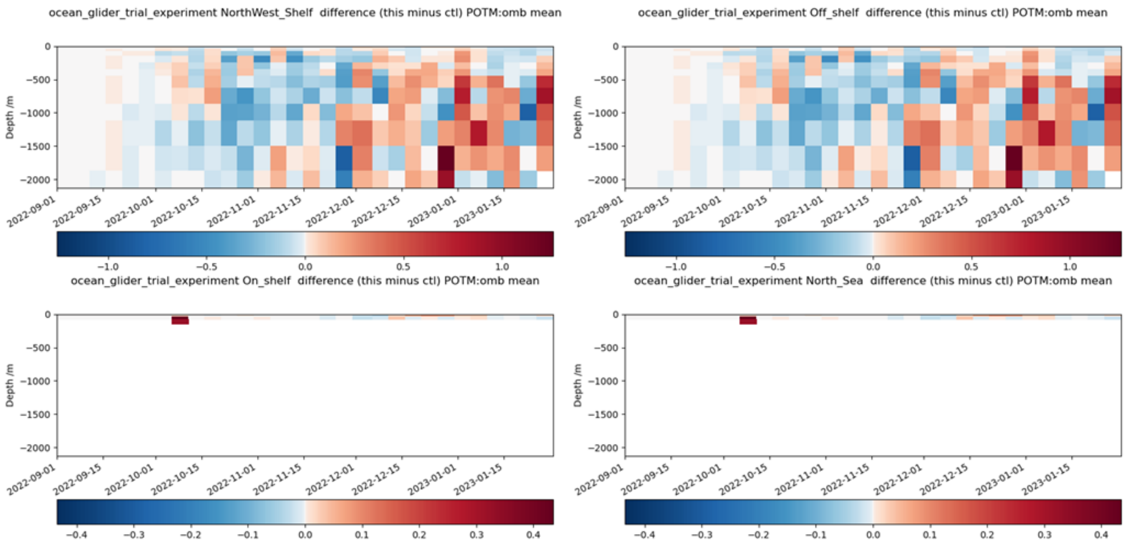

Figure 11: Hovmöller plot of mean omb differences for temperature fields at different depths. Whole AMM15 domain (top left), Off shelf (top right), On shelf (bottom left) and North Sea (bottom right).

Hovmöller plots of the temperature profiles over time were plotted (**Figure 11**); they show the mean observation minus background (omb) for the experiment model minus the omb statistics of the control. It can be seen that they display greater differences between the systems, initially showing a cooling and then a warming of the experiment in the deeper water regions over the whole domain and Off shelf.

A plot of the profiles averaged over time (**Figure 12**) shows that the larger regions with more observations at depth (whole domain and off shelf) have very similar results between the control and experiment.

For the shallower and smaller regions (on shelf and North Sea), the experiment appears to perform slightly better with reduced bias and RMSE values in the middle of the water column. Note that the control RMSE values go to zero below 100 metres due to a lack of available observations in this region (unsurprising given that the impetus behind this investigation was to address the sparsity of observations in the North Sea).

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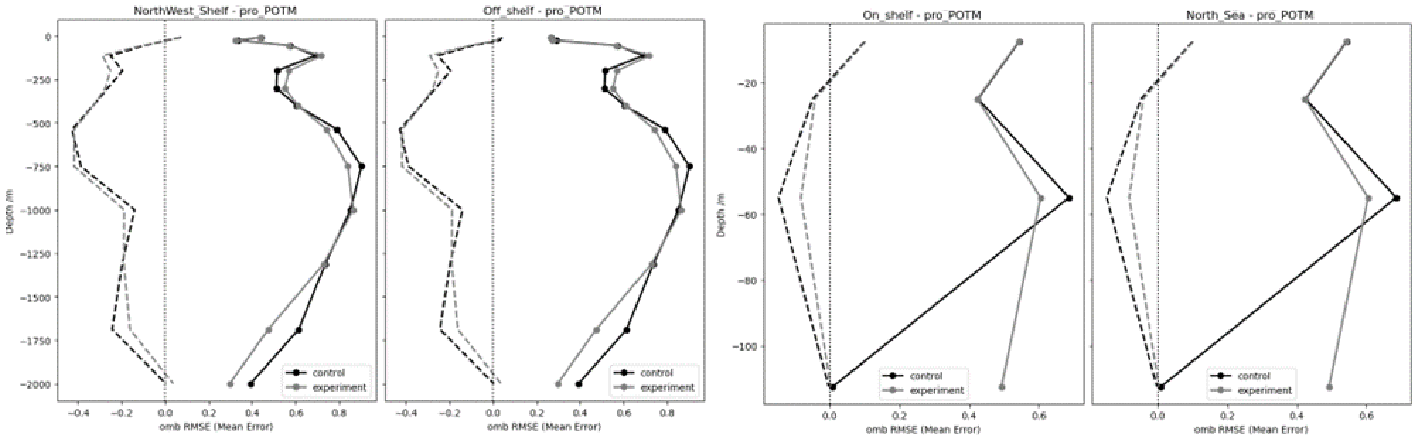

Figure 12: Time-averaged mean omb differences for temperature profiles. Solid line = RMSE. Dashed line = Mean Error: Whole AMM15 domain (far left), Off shelf (second left), On shelf (second right) and North Sea (far right).

Using the same methodology as for **Figure 11** to **Figure 12**, Hovmöller (**Figure 13**) and profile plots were generated for salinity data (**Figure 14**).

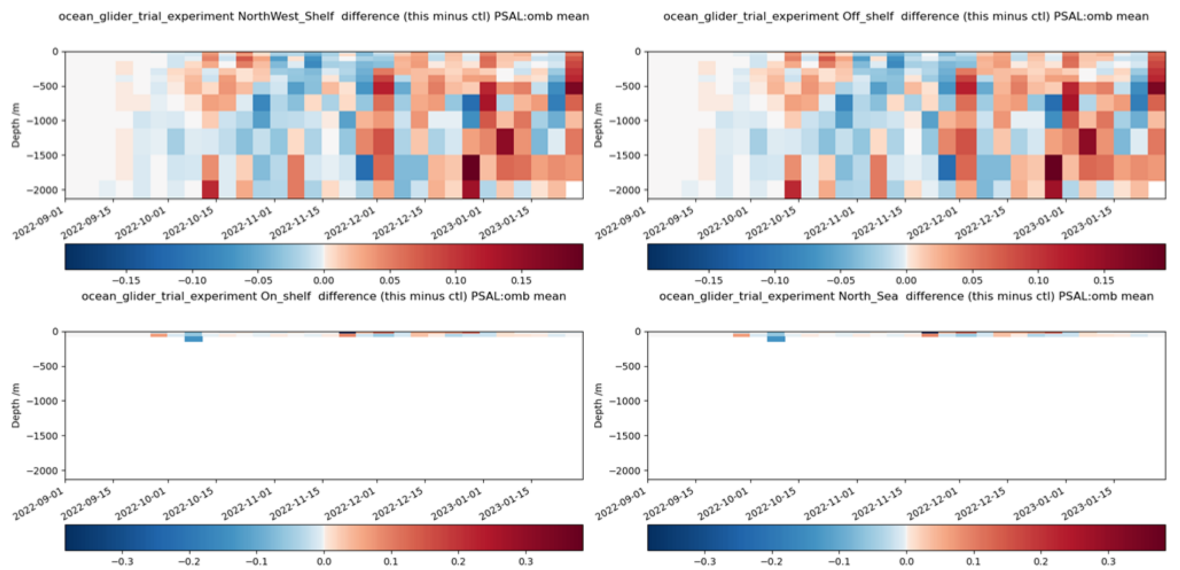

Figure 13: Hovmöller plot of mean omb differences for salinity fields at different depths: Whole AMM15 domain (top left), Off shelf (top right), On shelf (bottom left) and North Sea (bottom right).

The results from the Hovmöller plots (**Figure 13**) show that the experiment appears to be initially fresher at depths before becoming saltier. The salinity omb statistics for the control and experiment are very similar throughout the water column (**Figure 14**).

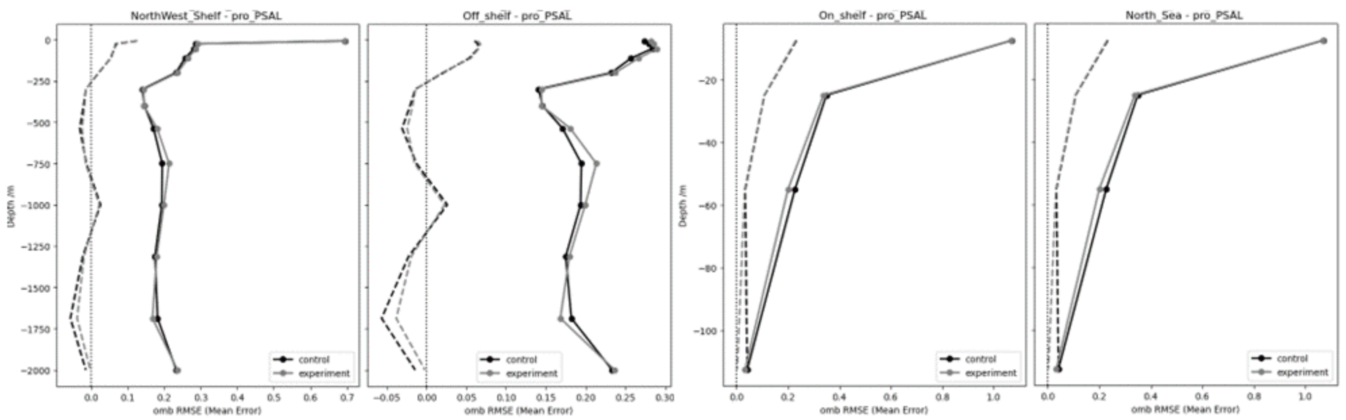

Figure 14: Time-averaged mean omb differences for *salinity profiles.* Solid line = RMSE. Dashed line = Mean Error*: Whole AMM15 domain (far left), Off shelf (second left), On shelf (second right) and North Sea (far right).*

Overall, the similarity of the results for the experiment and control indicates that the absolute temperature/salinity/sea level anomaly values have negligible changes in the off-shelf region. This supports the theory that the changes observed in the field plots (**Figure 4** to **Figure 7**) are more likely due to the locations of the values shifting (probably due to changes in the currents). However, the temperature profile data indicates a small improvement at depth (**Figure 12**).

5.3 Hovmöller plots from glider data

A second set of Hovmöller plots were produced using only the glider data (**Figure 15**). These examine shallower depths than those produced by Obsstats and so give a much clearer picture of the glider impact in their region of deployment.

The temperature plots (**Figure 15**) show that the experiment is consistently colder at depths and essentially the same as the control on the surface. Interestingly, the two systems start to converge at deeper depths as time goes by.

As stated before, it is known that September through to January sees the transition of the North Sea from a stratified to mixed state (van Leeuwen et al. 2015). If the control AMM15 were stratified and too warm in September, this would become less of an issue as the overall sea-temperature cools and becomes more well mixed into the winter. Therefore, the control in this scenario would converge with the experiment.

The salinity plots show that the experiment was also saltier than the control for all depths throughout the whole time period (**Figure 15**).

The information gleaned from the Hovmöller plots aligns with the field plot investigation outlined in **Section 5.1**: the bottom temperature fields start to converge in December 2022 (**Figure 4**) and the salinity (**Figure 6**) from the experiment remains saltier throughout the time period.

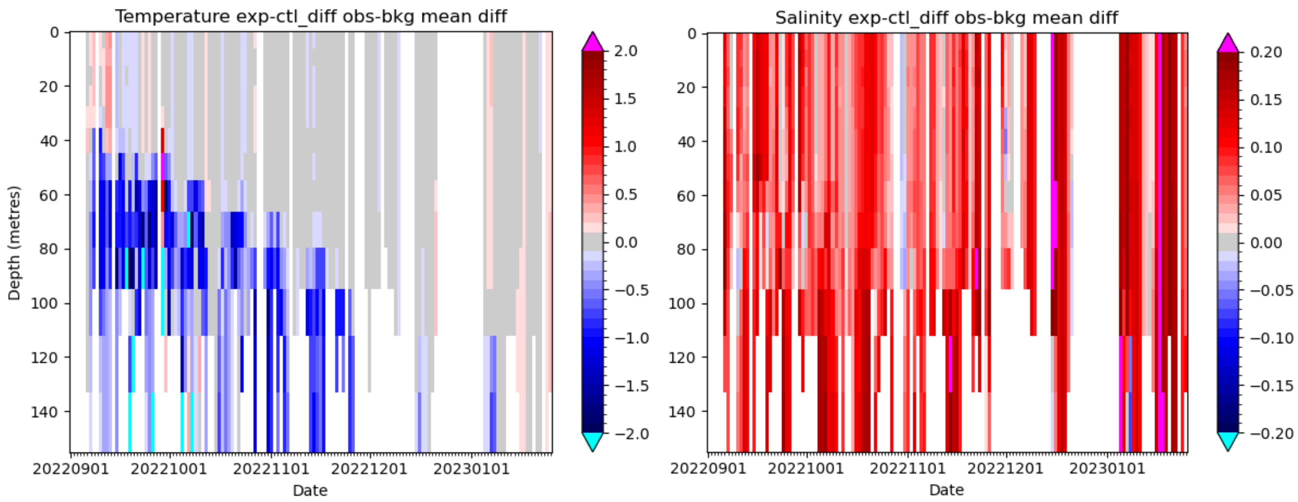

Figure 15: Hovmöller plots using only JONSIS region glider data for temperature (left) and salinity (right). The obs-bkg fields are extracted from each analysis and then the experiment and control are subtracted.

5.4 Comparison of AMM15 model forecasts to OSTIA reference dataset

OSTIA is a global SST analysis dataset produced in Near Real Time (NRT) in the Met Office. It is based on observational data from a wide range of satellites and in situ measurements and therefore OSTIA represents our most accurate image of global SSTs free from model influence. By comparing the AMM15 models forecasts to the corresponding OSTIA analysis for that day, an independent confirmation of the AMM15 forecast accuracy can be obtained.

Note that the North Sea domain used (**Figure 16b – insert**) is different to that used for Obsstats validation (**Figure 8**) since we wished to include the Norwegian Coast in our analysis.

The analysis average difference values for the whole AMM15 domain (**Figure 16a**) showed that the control had a negligibly lower bias compared to OSTIA than the experiment. A similar analysis for the North Sea domain showed that the experiment fared slightly better than the control (**Figure 16b**) and the benefit from the glider data persists and increases slightly throughout the model run.

The wider and the North Sea domains have opposite behaviours: AMM15 overall exhibits lower temperatures compared to OSTIA which drifts warmer during the forecasts, whereas the North Sea is warmer than OSTIA and drifts colder.

This behaviour is more pronounced in the experiment which exhibits more pronounced cooling; one theory is that this could be related to the cooler depth temperatures propagating to the surface.

Nevertheless, the differences between the AMM15 models and the OSTIA analysis are extremely small. While this means that we cannot conclude whether the experiment or control is superior, it does allow us to state that the gliders do not seem to have a detrimental effect on the experiment model.

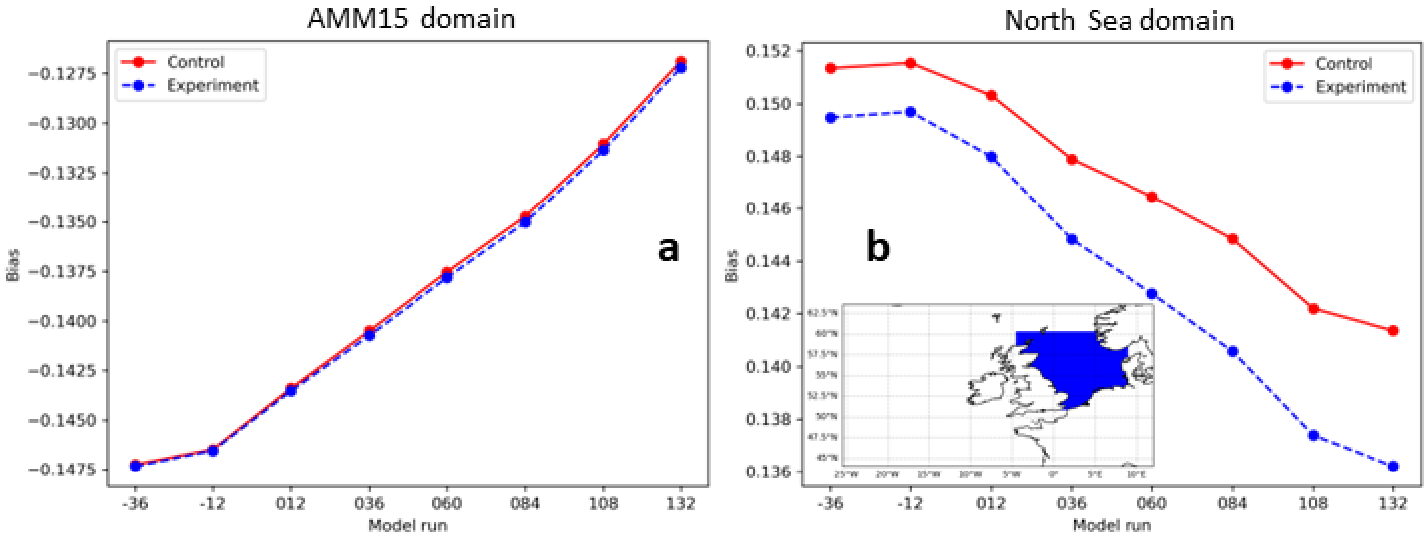

Figure 16: AMM15-OSTIA analysis mean difference for each model run. Calculate diff = mean(AMM15) – mean(OSTIA) for each day and run, which is then time averaged over the period 20220901-20230125. AMM15 domain (left). North Sea (right) – domain in insert.

6 Conclusion

We have investigated the impact on AMM15 of assimilating new ocean profile data from gliders operating on the JONSIS line in the North Sea. Two AMM15 systems were run: an experiment that assimilated the glider data and a control which did not.

Monthly averaged difference field plots (**Section 5.1**) and Hovmöller plots of the difference between the glider and model data (**Section 5.3**) point to the gliders making the experiment saltier throughout the water column and initially colder at deeper depths. Over time, the temperature of the control and experiment converged at progressively deeper depths. As stated earlier, during the September-January period the North Sea transitions from a stratified to mixed state (van Leeuwen et al. 2015). If there were increased mixing (and therefore smaller differences in temperatures throughout the water column) this would explain the convergence observed.

Large differences between the control and experiment were also seen away from the glider region. It is thought that these are mainly due to differences in the positions of features that are not constrained by the assimilation system. Validation using Obsstats (section **5.2**), which compares the model forecasts to observations, showed that the experiment and control are very similar. The SST timeseries (**Figure 9**) showed virtually no difference between the two systems. The temperature profiles showed some differences in the Hovmöller plots (**Figure 10**) and also the time averaged profiles (**Figure 11**), but no clear direction in favour of the control or experiment. A similar picture emerged when analysing Salinity and Sea Level Altimetry data – no system showed a clear advantage. Therefore, it can be concluded that the large differences away from the glider region are generally not systematic in nature and are therefore consistent with differences in the positions of features in the experiment and control.

Validation using the OSTIA SST dataset (**Section 5.4**) as a ground truth also showed that the two systems were very similar for the AMM15 domain as a whole but it was difficult to prove conclusively if the gliders improved the AMM15 model outputs. However, the gliders do not have a detrimental effect on the model either.

The results from on-shelf profile plots point to the gliders improving the model slightly (**Figure 12 and 14**) but it is difficult to prove conclusively since validation from deeper in the water column is hampered by a lack of independent in situ data. One way to infer this is through comparison to other forecast models. A Multi Model Ensemble is available for the North and Baltic seas where thirteen different ocean forecasting models from different institutes are compared (Golbeck et al. 2015). The same investigation also determined that the combined MME products were more accurate than individual forecasts, and so comparing a forecast with the MME median gives a good indication of that forecast's bias. The MME outputs are available online and show that the AMM15 model is too warm near the sea floor when compared to the MME Median (NOOS MME n.d.).Given that our investigation found that the glider data were making the AMM15 bottom temperatures cooler, this gives confidence that the gliders are having a positive impact.

Overall, the results of this preliminary investigation have demonstrated that glider data in the North Sea benefit the model and consequently the gliders are now in use operationally in the Met Office ocean and weather forecasting systems. The position of the gliders where two currents enter the North Sea has allowed the glider data to affect a broad region, which highlights how it is possible to maximise benefit from the investment in observational platforms by choosing the location in which they operate. The impact from the current glider deployment, however, does not extend to the southern part of the North Sea and therefore there is a need for other observations to constrain the temperature and salinity in that region. The small set of observations from a limited area have also resulted in unexpectedly large, albeit neutral, impacts in deep waters away from the glider area. Whilst these changes are consistent with perturbations to the position of ocean features, there are some persistent differences, such as freshening off the West Coast of Ireland, that might imply that the glider data are affecting the model's representation of North Sea circulation in an unexpected way, and therefore that further research could glean new information about the North Sea.

To account for seasonal changes, a follow up investigation is planned for data collected during the summer months. It is also expected that other gliders will be deployed in the UK region by other organisations, which will enable the impact of a larger glider observing system to be assessed. The availability of other gliders will also provide opportunities to withhold some data from the assimilation and help to answer questions such as:

1) Whether any impacts from the JONSIS glider extends further south, or if they are indeed completely limited by the Dooley current.
2) The accuracy of the experiment vs. control at different depths.

Further work is also planned to investigate the impacts of a glider augmented AMM15 on the UKV weather forecasts.

Met Office

7 Appendix

The videos and plots generated for the investigation are held on Zenodo and are open access under the Creative Commons Attribution licence

The videos are linked here:

https://doi.org/10.5281/zenodo.8358999

The plots are linked here:

https://doi.org/10.5281/zenodo.8359208

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