REFEREE #1

Manuscript title: *"The impact of a new high-resolution ocean model on the Met Office North-West European Shelf forecasting system". by M. Tonani et al.*

Bold: referee's comment
Not bold: author's answer

The referee's comments are copied in this document for ease of reading.

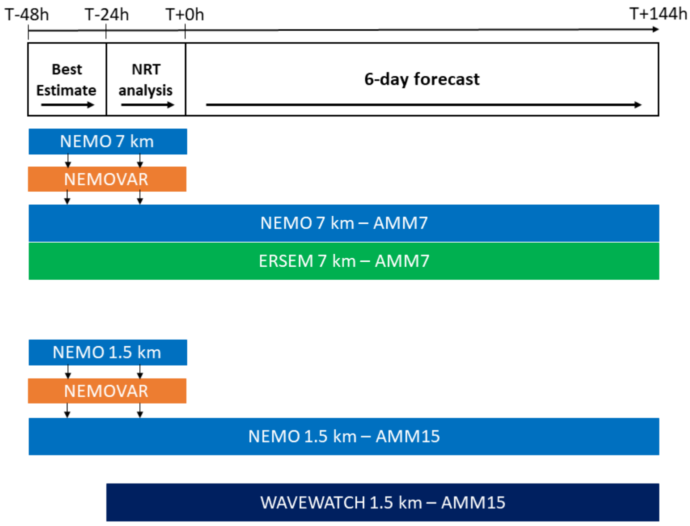
General comment:

The paper "The impact of a new high-resolution ocean model on the Met Office North-West European Shelf forecasting system" presents in a really useful and interesting way the main components of the high resolution regional ocean forecasting system and the validation protocol and results. Main novelties and innovative works in this study concern the high resolution of this regional forecasting system including data assimilation of the main available observations. As mentioned by the authors, it seems difficult to exhibit really significant improvements link to the higher resolution especially because the validation protocol is based on standard comparison between model and observations even if authors used specific high resolution observations based on glidersor HF radars. Nevertheless the study present an exhaustive comparison to available observations (assimilated or not) and validation diagnostics for most of the physical variables, these information are really useful for users of these operational forecast products and for developers of ocean forecasting system. I recommend the publication of this paper if the following minor revisions are taking into account in the final version.

1.Introduction

1. **It could be useful to have a schematic view of the operational schedule of the system. The figure 2 with more information for example**

Thanks for this suggestion. We had added this information, the new figure 2 is:



2. **Could you provide more precise information on the number of observations assimilated in the system thanks to the chosen assimilation cycles?**

From the manuscript:

"The system runs forecast cycle every day to provide 6-day forecast …. By assimilating observations in this way, the FOAM system incorporates information from considerably more observations than would be available in near-real time with a single 24-hr window, due to the addition of late-arriving observations".

The timeliness of the NRT observations could vary and be delivered with more than 24hr delay. For SST the delivery is usually within the 24-hr, therefore the impact is effectively zero for SST. NRT analysis (0h-24h) and Best estimate (24h-48h) have almost the same number of observations. The number of sub-surface profiles of temperature and salinity instead increases by ~15% by taking two days assimilation window instead of one. Given the low number of profiles this could be significant.

The number and quality of SLA observations increase in the file used for the Best estimate compared to the one available for NRT analysis. This is due to the production process of the SLA data, As described in Figure 2 in the Product User Manual (http://resources.marine.copernicus.eu/documents/PUM/CMEMS-SL-PUM-008-032-062.pdf) of this product.

The value available for the NRT analysis cycle are marked in orange in Figure 2 and are produced using altimeter fast-delivery input (Operational Geophysical Data Record, OGDR, or L2P Near Real Time). The value available for the Best Estimate cycle instead, in yellow, are produced using the altimeter real time data (Interim Geophysical Data Record, IGDR, or L2P Short Time Critical). The fast delivery input data have less measurements and lower accuracy.

Figure from CMEMS PUM:

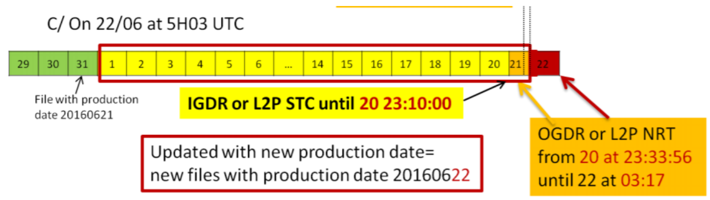


Figure 2: Data delivery flow for Global NRT SL-TAC products

Providing an estimation of the different number of observations and quality it's complicated by our assumption to assimilate data only where the depth is higher than 700m. An estimation of the differences between the SLA data available for the Best Estimate and the NRT Analysis are:

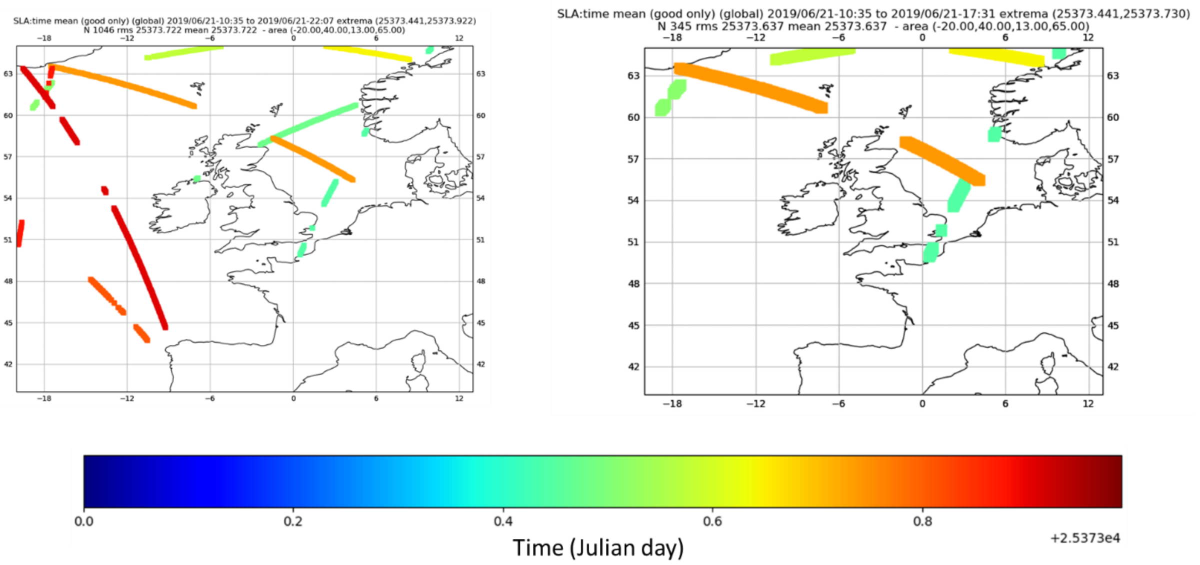


Figure: SLA observations available for the Best Estimate (left panel) and for the NRT Analysis (right panel). The value along the track represents the time associated with the measurements. The time is represented in Julian day. All the values taken after ~21:00 are not included in the NRT but are in the Best Estimate Analysis. Also measurements taken before 21:00, could be missing in the NRT data (e.g.: green line between 57 N- 61N).

3. **You mentioned the on going development of physic-biogeochemistry coupled system and the operational constrain. It's not the topic of the paper, but I suggest there is too much or not enough information for readers. Could you add few words about the time constrain and what kind of development is expected to reach the goal.**

The first version of the biogeochemical model coupled at 1.5km was made available at the end of year 2018. The preliminary tests required an extensive use of computational resources, not compatible with the operational requirements. One day (24 hours) of coupled model run required ~ 2.5 hours. The production of a full forecast cycle would have been around ~ 25 hours, for the 2 days with data assimilation and the 6 -day forecast. This number are prohibitive for a daily production cycle. These tests are running on the Met Office HPC – Cray XC40 super computer using 48 nodes and 1536 processors.

R&D activities are trying to improve the use of the resources and investigate different solutions for the coupling like a coarser time step or grid for the biogeochemical model.

The manuscript has modified:

"The upgrade of the NWS system to AMM15 does not yet include the biogeochemical component as the computational cost is prohibitive, because the production time exceeds the 24-hr for a full hindcast-forecast cycle."

2.System Development

2.1.Core model Description

1. **One specificity of the model configuration is the vertical coordinate system based on z*-σ. There is no justification in the description paragraph concerning the number of vertical levels which is the same than in the lower resolution system. Is there theoretical or experimental justification to reduce the rmax coefficient to 0.1 in this high resolution configuration and what is the expected impact (except the numerical stability)?**

The major aim of this model configuration is to resolve the Rossby Radius on the shelf, therefore the focus was on increasing the resolution from 7 to 1.5 km. more than increasing the vertical resolution.

The number of vertical levels is the same because the focus of this model is on the shelf (depth < 200m), where 51 z-sigma levels are enough for proving a very high vertical resolution. The resolution is of the order of 20cm the shallower part of the model domain, where the minimum depth is 10. More levels will increase the model vertical resolution in the deepest part of the domain, not on shelf (Siddorn et al., 20016). Another possible approach is using vertically adaptive vertical coordinates so that you focus resolution on the thermocline. This is done in other models but not here and will be considered in the future configurations.

All the technical details of the implementation and the validation of the model, without data assimilation, are presented in Graham et al., 2018 that is the precursor work to this paper.

The justification for the rmax choice is Graham et al. 2018a:

"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, rmax, where r =(hi −hi+1)/(hi +hi+1), and hi,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 rmax value. In regions where the smoothed model levels become deeper than the input bathymetry, these levels are then masked. Thermax value was chosen here 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".

2. **You impose a minimum of 10m depth on the bathymetry (this characteristic is also mentioned in the conclusion as a limitation), could you justify this choice, is only due to model stability?**

This is down to the tidal limits and lack of wetting and drying. 10m ensures that no locations dry out (e.g. Bristol channel).

This information is now added in the manuscript:

"The model minimum depth is forced to be 10m, due to the tidal limit and lack of wetting and dry. This choice ensures that no locations dry out, due to the tides."

3. How do you justify such difference (2 orders of magnitude) between the diffusion coefficient on tracer and advection?

These values we chosen over a series of sensitivity tests. We aimed to keep diffusion parameters as low as possible (due to resolving processes at higher resolution), opting for bi-laplacian diffusion along model levels primarily to ensure stability. For momentum, the value was chosen to account for processes that are still missing (e.g. smaller scale frictional processes). For tracers, we initially started with the same order of magnitude. However, these results appeared to be too diffusive, so following tests opted for a less diffusive value, but one that would still provide stable conditions under long simulations.

2.1.1Boundary and surface forcing

1. Could you add in the table 2 information concerning the difference of solar flux penetration in the two configurations and information on the tidal forcing at lateral boundaries

Yes, thanks for the correction. The tidal forcing information have been added to table 2. The differences concerning the solar flux penetration are in Table 1.

Updated Table 2:

Forcing	AMM7	AMM15
Surface forcing	Met Office Global Unified Model (MetUM) Atmospheric model NWP analysis and forecast fields, calculated in the MetUM using COARE4 bulk formulae (Fairall et al. 2003).	ECMWF Integrated Forecasting System (IFS)-Atmospheric Model High Resolution (HRES) operational NWP forecast fields using CORE bulk formulae (Large and Yeager 2009)
Surface forcing resolution	Horizontal grid: ~10 km (2560 x 1920 grid points) Frequency: 3 hourly mean fluxes of long and short wave radiation, moisture, 3 hourly mean air surface temperature but hourly 10m winds and surface pressure	Horizontal grid: ~14 km (0.125°x0.125°). Frequency: 3 hourly instantaneous 2m dew point temperature, surface pressure, mean sea level pressure, and 2m air temperature. 3 hourly accumulated surface thermal and solar radiation, total precipitation, and total snow fall.
River run-off	Daily climatology of gauge data averaged for 1950–2005. Climatology of daily discharge data for 279 rivers from the Global River Discharge Data Base (Vörösmarty et al., 2000) and from data prepared by the Centre for Ecology and Hydrology as used by (Young and Holt, 2007).	Daily climatology of gauge data averaged for 1980–2014. UK data were processed from raw data provided by the Environment Agency, the Scottish Environment Protection Agency, the Rivers Agency (Norther Ireland), and the National River Flow Archive (personal communication by Sonja M. van Leeuwen, CEFAS, 2016). For major rivers that were missing from this data set (e.g. along the French and Norwegian coast), data have been provided by the same climatology used by AMM7 (Vörösmarty et al., 2000 and Young and Holt, 2007).
Tidal constituents	M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, L2, T2, S1, 2N2, MU2, NU2 (15) from a tidal model of the North-East Atlantic (Flather, 1981).	M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, MN4 (11) from Topex Poseidon cross-over solution (Egbert and Erofeeva, 2002; TPX07.2, Atlantic Ocean 2011-ATLAS).
Lateral boundaries	Met Office FOAM North Atlantic (1/12°; 6 hourly fields) and CMEMS Baltic Sea (2km, 1 hourly fields).	
	AMM7 and AMM15 have Atlantic and Baltic boundaries in a different geographical location.	

2.2Assimilation method

Some information are missing in the description:

1. How is implemented the IAU method?

We have rephrased the manuscript sentence: "*The increments are applied to the model fields at each time-step using the incremental analysis update procedure (IAY, Bloom et al. 1996)*" with the following: *"After the assimilation step, the model is re-run for the same period with a fraction of the increments applied to the model fields at each time step (the incremental analysis update procedure, Bloom et al. 1996)*".

We hope this clarifies to the readers how the IAU method is implemented.

2. What is the SLA bias correction?

We have expanded page 7, line 14 adding the following text: “ *The Met Office implementation of NEMOVAR includes bias correction scheme for both SST and altimeter data. The SST bias correction aims to correct for biases in the observed SST due to the synoptic scale atmospheric errors in the satellite retrievals, while for SLA we apply a slowly-evolving bias correction to correct for errors in the MDT (Lea et al. 2008)”.*

3. How do you use the 2 correlation length scale in the assimilation scheme? Do you perform 2 analysis?

There is only one analysis. The correlation operator used in the specification of the background errors within NEMOVAR is a linear combination of functions with different length-scales (see Mirouze et al. 2016). This allow us to define a correlation operator that features high correlations within a short scale and weak correlations at large scales.

We added this reference is the manuscript.

Mirouze, I, Blockley, E. W., Lea,D.J., Martin, M.J., Bell, M.J.: A multiple length scale correlation operator for ocean data assimilation, Tellus A 2016, 68, 29744, http://dx.doi.org/10.3402/tellusa.v68.29744, 2016

4. In table 4, what are the differences between the 2 in situ data sources. How do you manage observation available in the two data bases?

The differences are in the data format, distribution protocol, timeliness. Some of the data sources are in common and therefore we perform a duplicate check before ingesting the observations in the analysis.

5. In table 4, there is no information on the mean dynamic topography used to assimilate the SLA.

We use the CNES-CL09 mean dynamic topography (MDT, Rio et al. 2011) to calculate observations of the SSH from the observed SLA which can be compared to our model SSH fields. We have added this information to table 4.

Data Assimilation	**AMM7**	**AMM15**
NEMOVAR version	V3	V4
SST bias correction scheme:	Offline observations-of-bias scheme. Reference dataset: in-situ.	Variational scheme in addition to observations-of-bias. Reference datasets: in-situ (drifters only) and VIIRS satellite data.
Correlation operator short scale: 3-times grid scale	~20 km	~5 km
Mean Dynamic Topography	CNES-CL09 mean dynamic topography (MDT, Rio et al. 2011)	

6. There is no information on methodology applied to assimilate the SLA in the model including tides.

We added the following to page 7, line 12: *"… as detailed in Table 4. The SLA observations assimilated in this model are provided through CMEMS and include the corrections necessary to add back the signals due to tides and wind and pressure effects necessary for use with a wind and pressure forced, tidal coastal model (King et al. 2018)".*

2.3Operational production

1. How is computed the QC error threshold for the observations?

The QC error threshold for the observations is defined on the base of the model-observation difference and varies with depth. Temperature and salinity have a different threshold error. The details on the background check are described in Ingleby et al., 2007. We added this reference to the manuscript. We corrected also the typo 1/3 with "*1/2*".

Ingleby, B., Huddlestone, M.: Quality control of ocean temperature and salinity profiles — Historical and real-time data, Journal of Marine System, Vol. 65, Issue 1-4, pp. 158-175, https://doi.org/10.1016/j.jmarsys.2005.11.019, 2007.

2. You provide output fields on a standard vertical grid, how do you provide the information at the surface (0m)? Is there a specific extrapolation to the surface?

The surface level is the model first level, we don't apply any specific extrapolation at the surface. We have substitute 0 with "*surface*" in the manuscript to avoid confusion.

3. Additional information concerning computational resources for this operational system could be useful (number of CPU, computer characteristics…)

These operational systems are running on the Met Office HPC – Cray XC40 super computer. The information in terms of number of nodes and processors used by each component of the system are in the following table:

System	Component	# of nodes	# of processors
AMM7	NEMO	8	256
	XIOS	--	--
	NEMOVAR	2	64
AMM15	NEMO	48	1536
	XIOS	8	256
	NEMOVAR	48	1536

XIOS is for the I/O of NEMO. The small size of AMM7 model grid doesn't require dedicated nodes for this task.

We have added this information in the manuscript.

4. More information could be added on figure 2 as for example, the observations, the atmospheric forcing, the restart and the assimilation and forecast sequence.

We have increased the number of information in figure 2, providing more details on the forecast production cycle. (see answer Question 1, Introduction).

4.Validation

4.1Tides

1. **M2 is the dominant tidal signal and probably the most important in an operational system for applications, user needs …. One unexpected result increasing the resolution is perhaps the degradation of the mean M2 solution. It will be important in this section to discuss this point and highlight origin of this degradation.**

AMM15has a higher mean error (few cm higher than AMM7) but a better RMSD than AMM7. This is explained in Graham at al. 2018:

"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."

Yes, the referee is correct, it is important to improve the tidal forcing of AMM15, in terms of tidal constituents and atlases. Research activities are ongoing to validate the impact of using a different model, FES2014, with many more tidal constituents.

4.2Sea Surface Height

The section concerning SSH, as it is, is not really useful and could be removed. But as the SSH is assimilated in the system it's important to quantify impact of these observations. I suggest to add few diagnostics in comparison to SSH as for example:

Statistic/comparison with altimetry in open ocean where observation are assimilated. Along track comparison could be performed. It's important to understand in the paper why SLA is assimilated in the system

Spatial power spectra to quantify spatial resolution of the system

Variability or eddy kinetic energy

The point of this short section is not to quantify the impact of assimilating SLA, this was done in King et al. 2018, but to verify that we can achieve similar accuracy (in terms of bias and RMSD) with the higher resolution model. The current altimeter assimilation is limited and there are plans to extend the assimilation into the shallow water regions which are tidally dominated.

We describe in the paper the procedure for the validation of the trial experiments for the pre-operational implementation of this system. The evolution of the model and data assimilation components are those described in Graham et al 2018 for the model and King et al. 2017 for the data assimilation.

4.3 Sea Surface Temperature

Temporal variability from seasonal cycle to high frequency is validated comparing model output to satellite observations and in situ time series. As expected there are few differences between the two models, main difference between the models being the horizontal resolution, even if the authors exhibit interesting higher frequency processes in the high resolution system. Even if it is not feasible with the observations why any spatial power spectra (or other diagnostics) has been performed to quantify differences between the 2 models?

As the referee is pointing out, it is difficult to identify an SST L4 product with a resolution comparable or higher than AMM15. We have done seasonal gradient maps from AMM7, AMM15 and OSTIA (not shown in the paper) and it's difficult to validate the increased variability of AMM15. The power spectrum plots shown in the manuscript show bigger differences between AMM15 and AMM7 during the autumn, probably due to the different stratification of the two models in that area. We copied here the details preferee#2 on figure9:

The power spectra shown in Figure 9 is for the FINO 3 buoy (number 2 in Figure 4). The buoy is in the German bight, where the bathymetry is shallow (~20m). The 12h energy peak overestimation is remarkable in SON (wrongly marked as DJF in the manuscript, now corrected), at the end of the summer when probably the two models have different stratifications. The water column is moved by the tides (M2 in the predominant tide) and this could bring to differences in the SST variability. The stratification is this area could also be enhanced by the fresh water contribution of two major rivers, Elbe and Weser. This hypothesis is supported also from the analysis of the map of SST gradients (not shown in the paper) where AMM15 shows stronger gradients than AMM7. Further studies are needed to understand better the SST variability in AMM5.

4.4Water Column

On figure 10 larger bias and larger differences between AMM15 and AMM7 is located at 100m depth. Is it linked to Mediterranean water? How do you explain this difference if the two configurations have the same constrains at the boundary and assimilates the same observations?

The large AMM7 bias is due to the vertical level discretization. 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, rmax. (Graham et al. 2018). AMM15 has a smaller value of Rmax (0.1) than AMM7 (0.3). The vertical discretization of AMM7, when the slope is too large over the shelf break, could end up with cells connected horizontally that are very different in vertical position. This means that the model is mixing in the horizontal sense water from two very different depths. Reducing the allowed slope, as it is in AMM15, prevents this artificial (or reduces) diapycnal mixing.

This is why AMM15 has a reduced bias at depth compared to AMM7.

4.4.2Moorings German Bight

Few more information or hypothesis will be useful to explain some description. –"The high frequency is better reproduced". Do you compute the correlation between the time series ? It's not clear on figure 11.

We added this sentence:

"The improvement is more evident in the summer (JJA) when AMM7 has a fresh bias of ~0.5 PSU while AMM15 has values very close to the observation."

No, we didn't compute the correlation between the time series.

-"at the bottom AMM15 is more accurate". Why? Is it link to the bathymetry or link to vertical projection of increments?

This is probably due to both. AMM15 bathymetry is more accurate and the higher resolution improves the representation of the model bottom, especially in these shallow areas.

-Table 8 : what is the depth of the bottom of each Buoy position?

Thanks for this comment, we added the depth of each buoy in table 8. The depth of these moorings varies from 18 to 35 m.

The updated table 8:

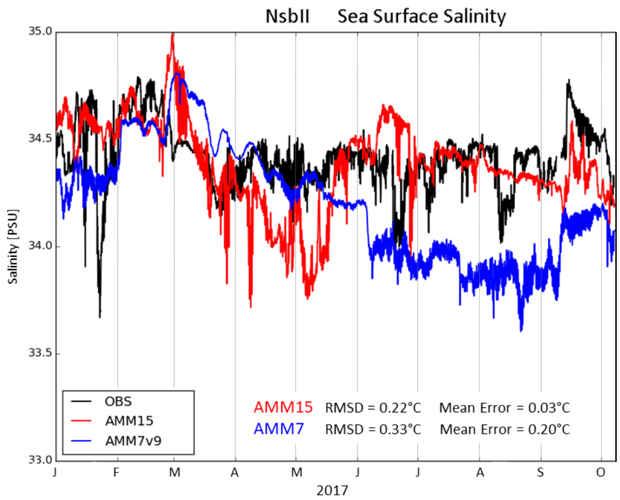
Buoy [bottom depth]	Temperature (C°)							
	Surface				Bottom			
	RMS Difference		Mean Errors		RMS Difference		Mean Error	
	AMM7	AMM15	AMM7	AMM15	AMM7	AMM15	AMM7	AMM15
1 Fino1 [25m]	0.32	**0.21**	**0.03**	-0.05	0.31	**0.21**	0.07	**-0.03**
2 Fino3 [18m]	0.38	**0.37**	**-0.02**	-0.04	0.96	**0.59**	-0.38	**-0.24**
3 NsbII [35m]	0.30	**0.25**	0.12	0.12	0.59	**0.49**	**-0.13**	-0.14
4TWEms [30m]	0.28	**0.26**	0.13	**-0.02**	0.28	**0.16**	0.11	**0.00**
5 UFSDeBucht [20m]	0.50	0.50	0.10	**0.01**	0.95	**0.75**	**-0.31**	-0.33
Mean value	0.36	**0.32**	0.07	**0**	0.62	**0.44**	**-0.13**	-0.15

Buoy [bottom depth]	Salinity (PSU)							
	Surface				Bottom			
	RMS Difference		Mean error		RMS Difference		Mean Error	
	AMM7	AMM15	AMM7	AMM15	AMM7	AMM15	AMM7	AMM15
1 Fino1 [25m]	1.17	**1.02**	0.97	0.97	1.10	**1.02**	0.95	**0.95**
2 Fino3 [18m]	1.06	**0.73**	**0.35**	0.48	0.90	**0.62**	0.53	**0.38**
3 NsbII [35m]	0.33	**0.22**	0.20	**0.03**	0.37	**0.17**	0.26	**0.03**
4 TWEms [30m]	1.05	**0.51**	0.85	**0.29**	1.08	**0.45**	0.89	**0.26**
5 UFSDeBucht [20m]	**0.99**	1.07	**0.55**	0.87	1.08	**1.02**	**0.86**	0.90
Mean value	0.92	**0.71**	0.58	**0.53**	0.91	**0.66**	0.70	**0.51**

-Figure9: why there is no model information in October? Add the correlation on the figure

Thanks for this comment, we have done a new picture, covering only the period January-October to avoid confusion. There are no measurements from the NsbII mooring in October, due to maintenance or malfunction of the sensor, the comparison model-observation is not possible. We double checked the other moorings and none of them is without interruptions.

We have added this information in the label of the new picture.



"*Figure 1: Sea surface salinity at the NsbII mooring for January-September 2017. Observations for October-December are not available*"

4.4.3Glider transects

Could you precise if the glider observations are assimilated or not in the system?

No, the glider observations are not assimilated in AMM7 nor AMM15. Both systems assimilate glider observations but not the profiles from the MASSMO4 2017 campaign.

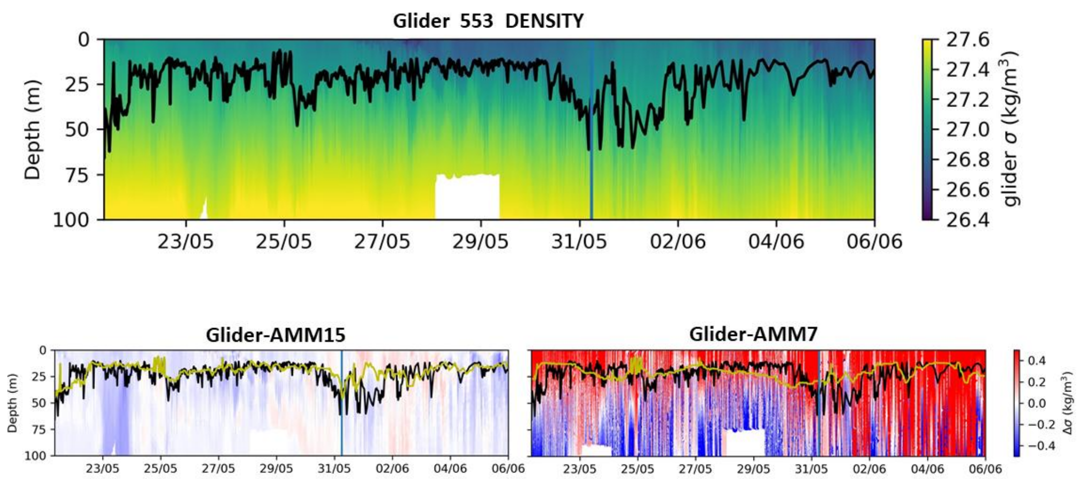
4.4.4Mixed Layer depth

I suggest adding the mixed layer depth for AMM15 and AMM7 on figure 15 for example.

Thanks for the comment, we have added the model MLD to these figures (Yellow line for AMM15 and AMM7 respectively. The black line represents the MLD from the observations).

We added this information in the manuscript:

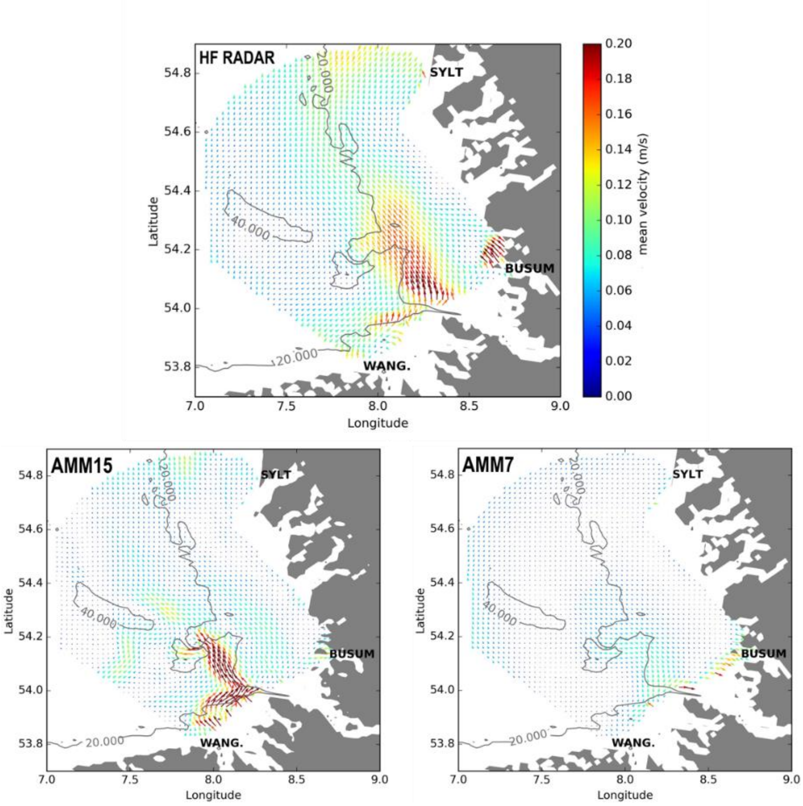
"*...with AMM15 and AMM7 in the corresponding locations (yellow line in Figure 15)*" and in the caption of the figures.



4.5Currents

The comparison with HF radar observations is very useful and seems to be more relevant to compare high and low resolution model outputs. I suggest adding the statistics (mean, rms, correlation on amplitude and direction) which seems to be encouraging for the high resolution model as it is explain in the text but without the figures.

Thanks to this comment we realised that we used in the manuscript the map of velocities before the cleaning of data instead of after. We substituted Figure 16 with the corrected Figure



We added the following text to the manuscript:

"One month, March 2017, of HF radar surface current velocity data were used to compare AMM7 and AMM15 in the German Bight where the bathymetry is shallow (Figure 4) and AMM15 is expected to performed better. The total surface velocity data from the COSYNA (Coastal Observing System for Northern and Arctic Seas) observing network (Gurgel et al., 2011), available through the EMODnet Physics data portal, are computed from radials of three HF radars installed on the islands of Sylt and Wangerooge, and in Büsum (as shown on Figure 6). Data are averaged every 20 minutes on a grid of resolution of ~3 km. At the operating frequencies used, the total surface velocities represent an integrated velocity over a depth between 1 and 2 m. Relative error provided with the dataset was used to keep only data with error smaller than 15%. Model output were interpolated at the time and locations when and where observations were available to avoid applying gap-filling technics.

Temporal coverage over the domain is larger than 75% everywhere except along the base line between Büsum and Wangerooge where the temporal coverage is ~29%."

Figure 17 is nice to exhibit differences between the 2 models. It could be even better to add map with high resolution observations on the same area. Is there any SLA, SST or ocean colour map that can be used to compare front and meso scale structure?

We agree with the reviewer, but we are not aware of any satellite map at a comparable resolution of AMM15. CMEMS has several products but the resolution varies from 1/4 -1/8 of degree with the exception of the ocean colour data from OLCI or the Odyssee SST L4 product. The ocean colour data have several gaps and it could be very difficult to make a comparison. We tried to look at the SST L4 data from Odyssee but since currents like the Norwegian coastal currents and the Scottish coastal currents are mainly salinity driven there is no signal in the SST maps, at least not at the resolution of the currents of AMM15.

We followed the suggestion of the referee#2 and we removed this part from the validation. We moved it at the end of the trial description, adding a new section.

5Conclusion and future developments

Something is missing in the conclusion, even if it is not obvious to validate and quantify improvement link to the higher resolution a discussion on expected improvements and link with user needs on this domain will be useful

We added the following sentence:

"*The users' benefit, using the newly improved European shelf product AMM15, will vary depending from their applications. Higher resolution currents fields with an improved representation of the coastal areas should improve the results of applications like drifting models simulating pollutant or oil spill dispersion and all the applications that need a high resolution currents field. All the acoustic applications, strongly depending on the density stratification and its variability, will benefit from these new products since they have a better representation of the water masses. A general positive impact is expected for most of the users like public bodies responsible for marine environmental regulation, aquaculture industries, marine renewable oil and gas industries*."

Typo, figures or format correction

1. **Section Boundary and Surface Forcing should be 2.2 and then 2.3 Assimilation method, 2.4 operational system**

Done

2. **Table 4 is cited before table 3**

Corrected

3. **Conclusion l 7 spatial/temporal**

Corrected

REFEREE #2

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Bold: referee's comment
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The referee's comments are copied in this document for ease of reading.

General comment:
The manuscript presents a detailed description of a new MetOffice ocean forecasting system at 1.5Km. This new high-resolution AMM15 system, together with the previous existing one AMM7 (at 7Km resolution), complete the physical ocean model system used to produce the CMEMS North-West-Shelf ocean forecast and analysis product. A comprehensive validation of both systems is provided. To achieve this validation, a comparative assessment of both model systems has been performed, using trial runs over 2 years period.
As the authors mention in the manuscript, in some occasions it is not an easy task to demonstrate the significant improvement of higher resolution model performances. The difficulties to assess the differences between both model systems, the higher and lower resolution ones, are mainly related to the scarcity of adequate observational data sources. Nevertheless, the present paper aims to do it, and it presents a complete general validation work. Besides, it is shown some additionally examples of model validation with very specific (but geographically limited) observational data sources, such as gliders and HF radar sites.

Despite the general scientific interest of the manuscript may be enhanced, the proposed paper is of interest in the context of the present CMEMS OS special issue. The complete description and exhaustive assessment of the new High-Resolution model system with respect to the previous existing one, is of interest for future, scientific and non-scientific, CMEMS NWS end-users, using products derived from the model systems here presented. Therefore, I do recommend publication of the manuscript after revision of some points.

For instance, I would ask the authors to justify in the revised manuscript some of the decisions taken to build the new 1.5Km model system set-up.
The authors should address in more detail some of the choice made related to:

4. **The model configuration (i.e.. why the authors keep in the high-resolution system the same tidal forcing (using the same 12 harmonics) then in the lower resolution system. Why they use the same vertical grid distribution)**

The major aim of this model configuration is to resolve the Rossby Radius on the shelf, therefore the focus was on increasing the resolution from 7 to 1.5 km. All the technical details of the implementation and the validation of the model, without data assimilation, are presented in Graham et al., 2018. That is the precursor work to this paper. The tidal forcing is going to be improved, in the next release of the AMM15 model that will include also the wetting and drying. Experiments are ongoing, using FES2014 and more tidal constituents. The number of vertical levels is the same because the focus of this model is on the shelf (depth < 200m), where 51 z-sigma levels are enough for proving a very high vertical resolution. The resolution is of the order of 20cm the shallower part of the model domain, where the minimum depth is 10. More levels will increase the model vertical resolution in the deepest part of the domain, not on shelf (Siddorn et al., 20016). Another possible approach is using vertically adaptive vertical coordinates so that you focus resolution on the thermocline. This is done in other models but not here and will be considered in the future configurations.

It's important to have a step by step incremental improvements protocol for updating an operational system, rather than changing many things all at once. This is the very first implementation of AMM15 in operations. This system or part its components will be improved on a yearly base in the future releases.

We have provided more technical information on this topic answering the specific questions here below.

5. **The data assimilation scheme used in the AMM15 system (i.e. why in a shelf model system, as the AMM15 is, it is assimilated SLA only outside the shelf; and how do the authors face the challenge of assimilating altimetric observations in high tidal environments)**

Providing more info on these points, of interest for ocean shelf modelers, the authors certainly will enhance the scientific interest of the paper for the ocean data assimilation and modelling community.

This first implementation of assimilation in the high resolution AMM15 followed the same scheme as used in the AMM7. Although the deep water areas of AMM15 are more limited than AMM7, and so the benefit of assimilating SLA may be small, this is a milestone on the way to assimilating SLA throughout the domain.
However, the assimilation of SLA observations in the deeper water still allows us to constrain the temperature and salinity in those regions, which then provides a better boundary condition for the shallow regions. As discussed in King et al. 2018, the assimilation of altimeter observations and T/S profiles is complementary, and in regions such as the NWS where profile observations are relatively limited, altimeter observations provide a valuable additional constrain on the density structure of the deep water regions.

Suggestions of text changes to improve the paper readability

I would recommend to moving any "pure" model-model comparisons, that is with no observational data source used as reference, from the Section 4, dedicated to validation results. Thus, the final comparisons shown on the surface currents patterns may be moved to another earlier section. I find these results very illustrative and give a good measure of the differences that we can expect from the new increased resolution model system (so, they should be included in the manuscript to show the different model performance achieved), but they do not provide any model validation (so, this text should be out of Section 4)

We thank the reviewer for this suggestion. We have modified the manuscript moving the "pure" model-model comparison in section 3:"*3.1 System performance: AMM5 vs AMM7*".
The sub-section on the "Currents" has been rename as "Currents in the German Bight" and moved up after the "Tidal flow" sub-section, because both based on the same HF radar observations.

The manuscript is now organized as follow:
Abstract

1. *Introduction*

2. System description
  2.1 Core model description
    2.1.1 Boundary and surface forcing
  2.2 Assimilation method
  2.3 Operational production
3. Trial experiments
  3.1 System performance: AMM15 vs. AMM7
4. Validation of the experiments
  4.1 Tides
    4.1.1 Tidal harmonics
    4.1.2 Tidal flow
  4.2 Surface currents in the German Bight
  4.3 Sea Surface Height
  4.4 Sea Surface Temperature
    4.4.1 Comparison with in situ and satellite
    4.4.2 Variability in SST
  4.5 Water column
    4.5.1 Temperature and salinity profiles
    4.5.2 Moorings in the German Bight
    4.5.3 Glider transects
    4.5.4 Mixed layer depth
5. Conclusion and future developments

As it is said before, I recommend publication of the manuscript after revision of the following points listed below.

Abstract

P1.15 "… (AMM7) that has been used for many years". Please, specify the context (CMEMS?, before Copernicus?)

We added this information in the text.

OLD:

"*The latest configuration to be put in operations, an eddy resolving model at 1.5 km (AMM15), replaces the 7km model (AMM7) that has been for a number of years.*"

NEW:

"*The latest configuration to be put in operations, an eddy resolving model at 1.5 km (AMM15), replaces the 7km model (AMM7) that has been used for eight years to deliver forecast products to the Copernicus Marine Service and its precursor projects*."

P1.18 "Trial experiments run with the low and high resolution systems in their operational configuration". Please, specify if this operational configuration includes Data Assimilation, or means just forecast runs.

The sentence has been reworded to specify that the trial experiments are done with data assimilation:

"Validation of the model with data assimilation is based on the results of two years (2016-2017) trial experiments run with the low ……"

1.Introduction

P1.35 In this paragraph, the authors mention human activities (industrial, farming, fishing) with climate change as source of impacts in the quality of water environments. All of them have certainly an impact, but I would suggest re-drafting the sentence, separating the impacts from climate change and the human-related activities, since they are at different levels.

We have re-worded that sentence as follow:
"*The increasing focus on understanding the marine environment in support of sustaining healthy and biologically diverse seas is also a considerable driver in these waters, where human activities like heavy industrial and farming activity, as well as fishing together with climate change effects, may have significant impacts on the quality of the marine environment.*"

P2.1 Include some reference to sustain the paragraph.

We added the following references :

She, J., Allen, I., Buch, E., Crise, A., Johannessen, J. A., Le Traon, P.-Y., Lips, U., Nolan, G., Pinardi, N., Reissman, J.H., Siddorn, J., Stanev, E., Wehde, H.: Developing European operational oceanography for Blue Growth, climate change adaptation and mitigation, and ecosystem-based management, Ocean Science, 12(4) 953-976 https://doi.org/10.5194/os-12-953-2016, 2016.

Siddorn, J.R, Good, S. A., Harris, C. M., Lewis, H. W., Maksymczuk, J., Martin, M. J., Saulter, A.: Research priorities in support of ocean monitoring and forecasting at the Met Office, Ocean Science, 12(1), https://doi.org/10.5194/os-12-217-2016, 2016.

P2.13 The (CMEMS?) operational forecasting for the North-West European Shelf (NWS). Other applications?

This operational configuration has been implemented for CMEMS. Several CMEMS users are using the product for a wide range of applications or for developing downstream products.

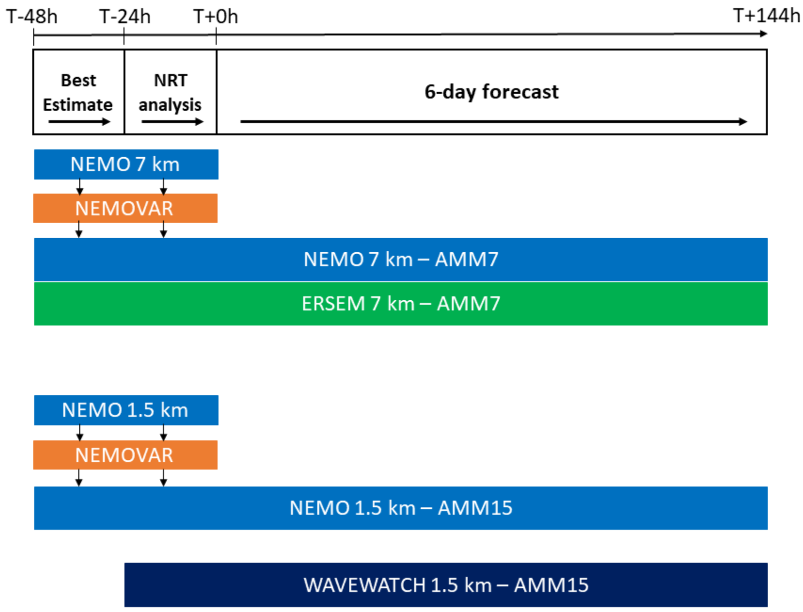
P2.15 To describe the geographical domain, the Figure 1 is referred. However, when a reader goes to this Figure, sees 2 different model domains: the AMM15 & AMM7, not mentioned yet and with not defined acronyms. It is a bit confusing for the reader at a first reading. The authors should improve this point: 1) moving after in the text the citation of this Figure 1, or 2) improving the figure caption to give more information on the features shown.

Thanks for the suggestion, we opted for improving the caption of figure1 :

Figure 2: EMODnet bathymetry, in meters (logarithmic scale), showing the NWS high resolution, AMM15, model domain. The red line defines the NWS low resolution, AMM7, model domain. The yellow dotted box is the domain covered by the AMM15 products delivered on a regular grid to the Copernicus users. Figure modified from Graham et al. (2018). The bathymetry colour range has logarithmic scale.

P2.24 From this line up to the end of this Introduction Section, the authors mention different components of the CMEMS NWS system (i.e: ocean physical model, data assimilation system, together with the biogeochemical model coupled into it). Also, there is a mention to a wave model system, and to an ocean-wave-atmospheric coupled system. In order to enhance the understanding of the systems and its multiple connections with other applications, here outlined, the authors should include a figure showing a schematic view of the CMEMS NWS operational forecast system, here described. This extra figure suggested may be included as part of the present Figure 2. This way, the number of figures is not increased and the present Figure 2, what currently provides certainly very few information, is enhanced.
I would also miss in this part of the manuscript some reference to the CMEMS operational products generated through the model systems here described (with citation to their documentation).

Thanks for this suggestion. We had added this information in figure 2:



We have added the list of the CMEMS products at the end of the introduction:

"The7km products (AMM7) delivered though Copernicus are:

- *NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_001_b (http://marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-001.pdf);*
- *NORTHWESTSHELF_ANALYSIS_FORECAST_BIO_004_002_b (http://marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-002.pdf).*

The1.5km products (AMM15) delivered though Copernicus are:

- *NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_013 (http://marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-013.pdf);*

- *NORTHWESTSHELF_ANALYSIS_FORECAST_WAV_004_014 (http://marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-014.pdf).*

This study is focused on the product NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_013 and its inter-comparison with NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_001b."

P2.30 With respect to the latest system mentioned in this paragraph: the oceanwave-atmosphere coupled system, is this currently an operational one? or is it in a pre-operational phase? Or only for research purposes?
This is system is just for research purposes at present, as written in the text "*coupled ocean-wave-atmosphere research system*".

P2.37 Please, include some quantitative numbers or estimations to support the adjective "prohibitive".

We added this sentence to the manuscript**:**
", because the production time exceeds the 24-hr"

2.System Description
P3.10 Use CMEMS instead Copernicus.
Done
P3.19 The new AMM15 system uses the same vertical grid resolution than the AMM7 one. Why it was not considered to increase the vertical resolution consistently with the horizontal one? Is the present vertical resolution with 51 levels enough? Have the authors performed any sensitivity test to evaluate the impact of an enhancement of vertical resolution? Or the decision to keep the vertical resolution unchanged is more a matter of computational resource availability? Any comment on this point?
The increased horizontal resolution moving from AMM7 to AMM15 allows a step change in the ability to represent small-scale processes, but there remains work to be done to address biases in the vertical representation in the shelf seas (detailed in Graham et al. 2018a). These are influenced by many factors including the vertical mixing scheme, advection, light attenuation scheme, and wave-mixing parameterizations. Simply increasing the vertical resolution was not expected to lead to any improvements without first addressing these physical mechanisms (see also answer to the first general question).

P4 No reference in the text to Table 1?
Thanks, we added the reference to Table1 in the manuscript.

P5.9 Are 12 tidal harmonic constituents enough to rightly reproduce the tides in a region such as the one covered by the high resolution AMM15 model, that is marked by shelf shallow waters with very high tidal environments? Can the authors justify why the same 12 harmonics are used in both systems? Since the objective is to model the region at a very high resolution, it would not be worthy to count with an improved higher resolution tidal forcing (the original TPX harmonic are at a 1/12º resolution). Furthermore, please, include in the manuscript the list of the 12 harmonics used (this list of harmonics can be provided directly in the text, or in Table 2).

We thank the author for this comment. There is a typo in the manuscript, the tidal constituents are 11, not 12 (We have corrected the manuscript).
The first implementation of AMM15 as been set up as much as possible as AMM7 for understanding the impact of the increased resolution. The number of tidal constituents has not been increased. AMM15 has less tidal constituents than AMM7 due to the different model used (see the updated Table 2 here below).
It is worth to note that the tidal boundaries in AMM are in the deep (off shelf) region for the most part (excepting short stretches where they cross the continental shelf). The higher modes are less important in the deep. They are significant only in the shallows where a large component of them are going to be locally generated by the interaction of the primary constituents with the bed and coastline rather than remotely forced at deep water boundaries.
Yes, the referee is correct, it is important to improve the tidal forcing of AMM15, in terms of tidal constituents and atlases. Research activities are ongoing to validate the impact of using a different model, FES2014, with many more tidal constituents.

The updated version of Table 2 is:

Forcing	AMM7	AMM15
Surface forcing	Met Office Global Unified Model (MetUM) Atmospheric model NWP analysis and forecast fields, calculated in the MetUM using COARE4 bulk formulae (Fairall et al. 2003).	ECMWF Integrated Forecasting System (IFS)-Atmospheric Model High Resolution (HRES) operational NWP forecast fields using CORE bulk formulae (Large and Yeager 2009)
Surface forcing resolution	Horizontal grid: ~10 km (2560 x 1920 grid points) Frequency: 3 hourly mean fluxes of long and short wave radiation, moisture, 3 hourly mean air surface temperature but hourly 10m winds and surface pressure	Horizontal grid: ~14 km (0.125°x0.125°). Frequency: 3 hourly instantaneous 2m dew point temperature, surface pressure, mean sea level pressure, and 2m air temperature. 3 hourly accumulated surface thermal and solar radiation, total precipitation, and total snow fall.
River run-off	Daily climatology of gauge data averaged for 1950–2005. Climatology of daily discharge data for 279 rivers from the Global River Discharge Data Base (Vörösmarty et al., 2000) and from data prepared by the Centre for Ecology and Hydrology as used by (Young and Holt, 2007).	Daily climatology of gauge data averaged for 1980–2014. UK data were processed from raw data provided by the Environment Agency, the Scottish Environment Protection Agency, the Rivers Agency (Norther Ireland), and the National River Flow Archive (personal communication by Sonja M. van Leeuwen, CEFAS, 2016). For major rivers that were missing from this data set (e.g. along the French and Norwegian coast), data have been provided by the same climatology used by AMM7 (Vörösmarty et al., 2000 and Young and Holt, 2007).
Tidal constituents	M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, L2, T2, S1, 2N2, MU2, NU2 (15) from a tidal model of the North-East Atlantic (Flather, 1981).	M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, MN4 (11) from Topex Poseidon cross-over solution (Egbert and Erofeeva, 2002; TPX07.2, Atlantic Ocean 2011-ATLAS).
Lateral boundaries	Met Office FOAM North Atlantic (1/12°; 6 hourly fields) and CMEMS Baltic Sea (2km, 1 hourly fields).	
	AMM7 and AMM15 have Atlantic and Baltic boundaries in a different geographical location.	

P5.18 The authors mentioned that ECMWF IFS data is used as forcing in the AMM15 system, whereas the AMM7 uses the MetUM forcing. The move to the ECMWF forcing is justified as a requirement of the CMEMS service. However, the IFS data have lower resolution than the MetUM (around 14 Km in the former, instead of the 10 Km of the later). Apart of this "service" reason, can the authors comment on the impacts that move from a higher resolution forcing to a lower one has in the ocean model solution? Furthermore, later the authors mention that using IFS there is a lost in terms of analysis frequency availability (from 3h to 6h). Can the authors provide some quantification of the impact related to the change in the forcing? It is certainly not very intuitive for a reader to understand how when a new higher resolution model system is being set up, it is decided to use a lower resolution atmospheric forcing. Can the authors explain any positive impact of the change in the atmospheric forcing to support the decision?

Yes, we agree with the referee that we need to run impact studies to assess the impact of the different resolution in the atmospheric forcing. These studies were not part of the pre-operational implementation, therefore are not discussed in this paper. These experiments are carried out in the frame of a UK project. As soon as available these results will be shared with CMEMS. If the impact of the coarser spatial resolution is significant we could switch to the Met UM forcing in a future evolution of the operational system.
The ECMWF-IFS analyses are not used, we use only 3-hr forecast fields. We are planning to switch to hourly ECMWF-IFS products by the end of 2020.

P7.11 It is stated that there is SLA assimilation both in MM7 and MM15 systems, and in both cases, for regions with bathymetric depths > 700m. In the case of the MM7 configuration this option can make sense, since extended deep water areas are covered. However, on the contrary in the case of the AMM15 shelf model system, this set-up option seems to result in a SLA data assimilation limited to a very narrow area (and very close to the open boundaries!). Can the authors explain in more detail the impact of the SLA data assimilation approach performed on the AMM15 shelf system? Can the authors provide a measure of the benefit of assimilating SLA data assimilation on such a limited (and so close to the boundaries) area? The authors should explain better the potential gain of using such limited SLA data assimilation with respect to a free non-assimilative approach.

This first implementation of assimilation in the high resolution AMM15 followed the same scheme as used in the AMM7. Although the deep water areas of AMM15 are more limited than AMM7, and so the benefit of assimilating SLA may be small, this is a milestone on the way to assimilating SLA throughout the domain.
However, the assimilation of SLA observations in the deeper water still allows us to constrain the temperature and salinity in those regions, which then provides a better boundary condition for the shallow regions. As discussed in King et al. 2018, the assimilation of altimeter observations and T/S profiles is complementary, and in regions such as the NWS where profile observations are relatively limited, altimeter observations provide a valuable additional constrain on the density structure of the deep water regions. Without additional experiments, the contribution of altimeter observations is difficult to quantify.

P7.13 Table 4 cited before Table 3. Please, try to respect the order in Figure and Table citation.

Thanks, we swapped table 3 and table 4 and the corresponding cross-references.

Table 4. In the column of Data source: 1st arrow: "CMEMS –INS-TAC" may be substituted by "CMEMS-INS-TAC Product:" The same for "GTS" ("GTS Product:"?); 2nd arrow: "CMEMS-SL-TAC Product:" 3rd arrow: "Product from the Group for High Resolution Sea Surface Temperature (GHRSST):"

Thanks for this comment. We modified changed Table 4 taking into consideration this comment. The column "Data source" is now "Data source/Products":

Type	Fields	Platforms/Satellite	Data source/Product
IN SITU	SST Temperature and salinity profiles	• Ships • Drifters • Fixed moored arrays • Gliders • XBTs • CTDs • ARGO • Ferry boxes • Recopesca buoys* • Thermosalinograph	GTS; http://www.wmo.int/pages/prog/www/TEM/GTS http://marine.copernicus.eu/ INSITU_GLO_NRT_OBSERVATIONS_013_030
SATELLITE	SLA Along Track* **along with the corrections necessary for the use with a wind and pressure forced, tidal coastal model. SLA are assimilated only in deep regions (> 700m).*	• Cryosat-2 • Altika • Jason 3 • Sentinel 3a	http://marine.copernicus.eu/ SEALEVEL_EUR_PHY_ASSIM_L3_NRT_OBSERVATIONS_008_043
	SST L2p/L3c	• NOAA-AVHRR • MetOp-AVHRR • SEVIRI • VIIRSG • AMSR2	Group for High-Resolution Sea Surface Temperature (GHRSST) www.ghrsst.org

P9.15 What is it done with the info on the profile quality check performed? Any communication established with the observational data producers? (a kind of blacklisting?).

We store all the information on the quality check in a set of files called "feedback files" (each for each type of observations: sub-surface profiles of temperature and salinity; SLA; SST). We are working with the CMEMS Product Quality Cross-Cutting working group to identify a CMEMS standard for conveying this information to the data producers.

P9.19 Do the authors foresee any problem in using OBCs from different model data sources? Are they consistent? Can be a source of problems due to volume conservations issues?

The two models providing the boundaries are not consistent and this is the reason why we don't force the Baltic Boundary with SSH (The Baltic model is not constrained by data assimilation while the North Atlantic is). The Atlantic model providing the boundaries and AMM are both constrained by the assimilation of the same SLA data, this should avoid major discrepancies at the Atlantic boundary. The forcing at the boundaries is an active research topic for our model and hopefully in the future we can improve the parametrisation we are using now even if the problem is more worrying when producing reanalysis or climate simulations spanning over a much longer number of years than a short-term forecast system.

P9.37. The production process takes approximately 4 hours. How many CPUs are used during the process? Can the authors include here a computational cost estimation?

These operational systems are running on the Met Office HPC – Cray XC40 super computer. The following table describes the number of nodes and processors used by each component:

System	Component	# of nodes	# of processors
AMM7	NEMO	8	256
	XIOS	--	--
	NEMOVAR	2	64
AMM15	NEMO	48	1536
	XIOS	8	256
	NEMOVAR	48	1536

XIOS is for the NEMO I/O. The small size of AMM7 model grid doesn't require dedicated nodes for this task.

We added this information to the manuscript.

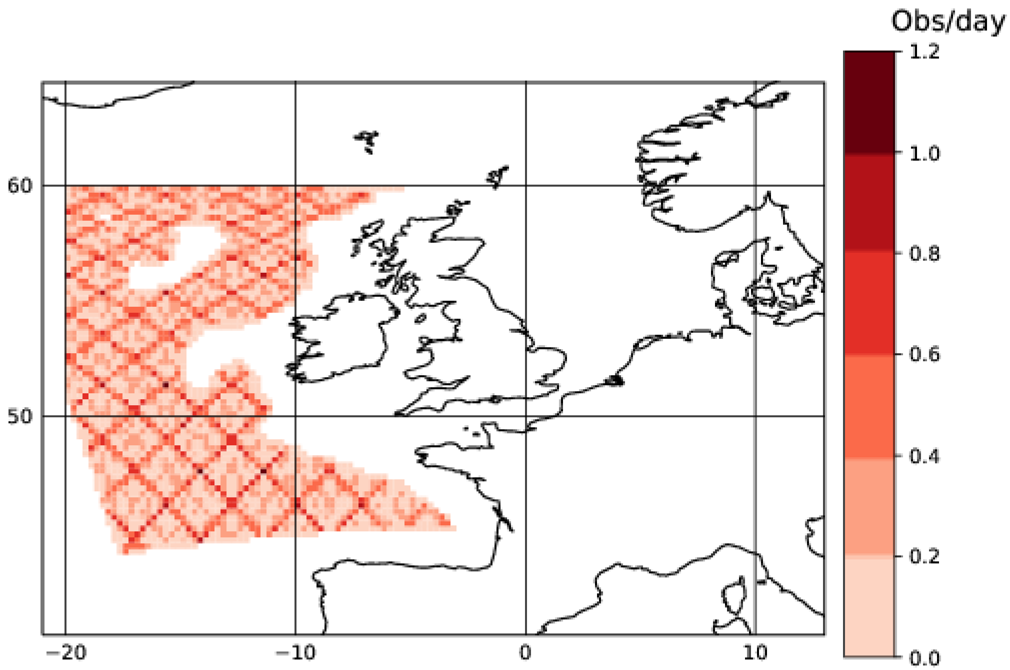
Figure 2: Include here info on the ECMWF IFS forcing (analysis/forecast) used. Complete this Figure, as suggested in previous comment, showing a schematic view of the CMEMS NWS operational forecast system described.

Yes, the figure has been updated, please see comment P2.24
We use only the forecast fields from ECMWF-IFS, due to the coarse time resolution of the analysis (6-hr), as specified in table 2 and at P6.2 of the manuscript: "*The IFS analysis is available only at a low temporal resolution (6 hours) therefore the decision was made to force the system using forecast fields only (3 hourly), from the 00:00 UTC forecast base time*".

3.Trial Experiments

Figure 3. Number of observations used for assimilation. The panel on the SLA show effectively the satellite SLA observations available. However, this panel can mislead the reader, since the data assimilation is applied only on areas with depths > 700m. I suggest the authors will identify in the plot the area where SLA is effectively assimilated in AMM15 system.

Thanks for the comment, the new version of the Figure 3 shows now only the assimilated SLA obs:



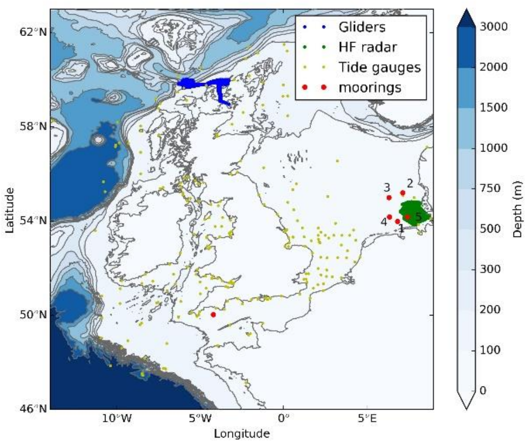
The authors should consider the possibility to include in this section the analysis of the differences between the dynamical patterns modelized by the 2 different model systems, currently included in the Validation Result section. This point is suggested below.

Yes, thanks for the comment. We have taken this suggestion into consideration as described in detail at the beginning in the general comments.

4.Validation of the experiments

Figure 4. specify also here the locations where observations from coastal tide gauges are available for the tidal validation.

Thanks, Figure 4 has been updated with the location of all the tide gauges used for the tidal validation (yellow dots).



2 figures are dedicated to display location of observational data sources used in the paper. The Figure 3 shows those observations used in the data assimilation. On the other hand, the Figure 4

displays other observational data sources used in the validation process. Where are the coastal tide gauges? I guess they are not assimilated, however they are not depicted neither in Figure 4. Furthermore, the reader founds later in Table 6 (where results from the validation of different variables are shown) results for the M2 tidal harmonic and there it is said that validation is done for the full domain. However, no info on the location of the tide gauges used is provided up to that moment. Later, already in Section 4.1, in the Figure 5 there is a map of model-obs differences in M2 amplitude and phase. Please, clarify a bit the geographical information on the tide gauge locations.

Thanks for pointing out this inconsistency. Yes, it's correct, the tide gauges data are not assimilated. We have updated Figure 4 adding the tide gauge location (see the figure in the comment above).

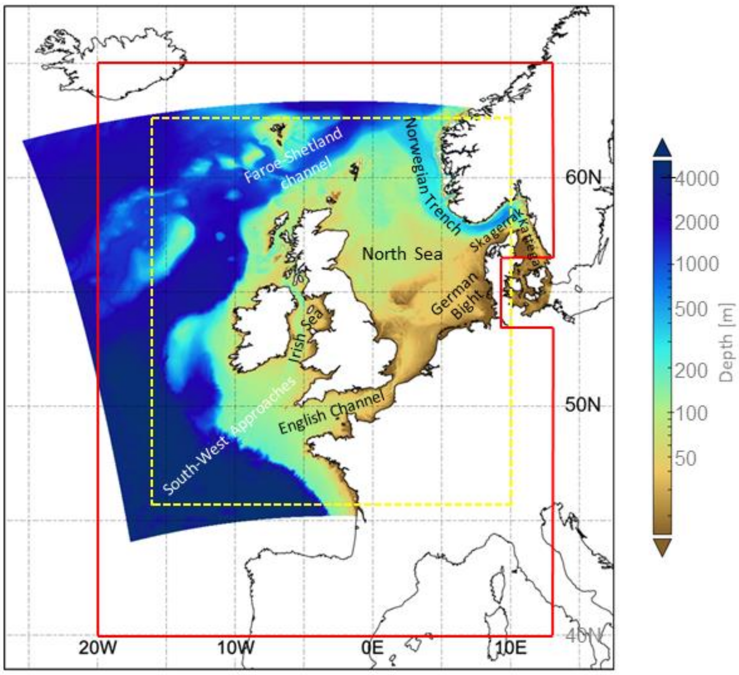
P14.11 Tide gauges observations from BODC. "The number of tides gauges taken into consideration for AMM15 and AMM7 is the same, therefore the coastal buoys"; are the authors here referring to tide gauges? Or to buoys? Can the authors provide more details about the tidal observations offshore, where do they come from? (From platforms?, pressure sensors?). More explanation about the tidal measurements from the BODC it may help the reader.

Thanks for the comment, it's not appropriate calling "buoys" the tide gauges data. We have corrected the manuscript as follow:

"*The number of tide gauges taken into consideration for AMM15 and AMM7 is the same, therefore the coastal data, ….*"
The tide gauges data are from BODC (https://www.bodc.ac.uk/data/hosted_data_systems/sea_level/uk_tide_gauge_network/) and from the North West Shelf Operational Oceanographic Service, NOOS, data portal (http://noos.eurogoos.eu/). All the data are from tide gauges.
We have included these two web sites into the manuscript.

P15.13 Suggestion to ease readability: in one of the maps, for instance in Figure 1, the authors should detail all the geographical names mentioned in the text (i.e. German Bight). This reference to geographical features will ease the reading of the paper to those potential readers not familiar with the regional geography.

Thank for the comment, done



P16.5 The authors shown in the paper (section 4.1.2) some results of the model validation with a HF Radar system. The results are only for 1 month (March 2017). If the authors have 2 years model runs, why do they perform/show a so short temporal coverage of the model- HF Radar validation? Due to observation availability? Please, explain reasons in the manuscript.

We decided to focus our high resolution model validation on small areas and short time period, for both the glider and the HR radar observations. Both observations could be available for longer period and in different areas, but we have decided to stay focus on a short period to understand the impact of the high resolution and what is an adequate protocol to assess the quality of a high resolution model. As written in the manuscript at P1211 " …*have the benefit of providing an understanding of the impact of the high resolution locally on small area and short time scales*". This validation will be extended to assess the future evolution of the AMM15 system, since we proved it's useful and complementary to the standard validation protocol.

Figure 6 shows the results of the model-HFRadar validation. In this figure, it is shown some statistics fields (RMSD, Bias, Veering) limited to the HF Radar spatial coverage. However, the reader have no information about the number of observational data that support these statistics. Do the HF-Radar system provide exactly the same number of observations everywhere? If yes, please detail what gap filling methodology is being applied. If not, please, show the % of HF-Radar data availability. I guess the 3 names referred in this figure 6 corresponds to the HF Radar sites. Please, detail in the Figure Caption.

Thanks for this comment, we added the requested information in the manuscript,

"*One month, March 2017, of HF radar surface current velocity data were used to compare AMM7 and AMM15 in the German Bight where the bathymetry is shallow (Figure 4) and AMM15 is expected to performed better. The total surface velocity data from the COSYNA (Coastal Observing System for Northern and Arctic Seas) observing network (Gurgel et al., 2011), available through the EMODnet Physics data portal, are computed from radials of three HF radars installed on the islands of Sylt and*

Wangerooge, and in Büsum (as shown on Figure 6). Data are averaged every 20 minutes on a grid of resolution of ~3 km. At the operating frequencies used, the total surface velocities represent an integrated velocity over a depth between 1 and 2 m. Relative error provided with the dataset was used to keep only data with error smaller than 15%. Model output were interpolated at the time and locations when and where observations were available to avoid applying gap-filling technics. Temporal coverage over the domain is larger than 75% everywhere except along the base line between Büsum and Wangerooge where the temporal coverage is ~29%."

Yes, the three names correspond to the HF radar sites, thanks for this comment. The caption of the picture includes now this information.

P18.13 The in-situ measurements are from buoys and ships of opportunity. Please, detail if "buoys" means fixed moorings, surface drifters or ARGO profilers.

Thanks for this comment, we have corrected the manuscript as follow:
"*The in-situ measurements are from different instruments, as detailed in* ***Error! Reference source not found.****.*"

P19.4 A Butterworth filter. Please, explain in more detail or add a reference.

Thanks for the comment. We have modified the manuscript as follow, including a reference and enhancing the explanation:

"*A Butterworth filter (Butterworth, 1930) has been applied to the hourly model and observed SST data, using a cut-off for the filter at 5 days which removes the large scale synoptic and seasonal signals, leaving the internal dynamics and the wind driven signals, as well as the tidal frequencies*".

S. Butterworth, "On the Theory of Filter Amplifiers," Experimental Wireless and the Wireless Engineer, Vol. 7, 1930, pp. 536-541.

P19.20 AMM7 and AMM15 models provide very similar values of SST, probably due to the data assimilation of SST that brings models close to the observations. Can the authors include in the paper any SST timeseries analysis as the one here shown for the 3 proposed sites, but in a station, whose SST observational data would not be assimilated? See some independent validation would certainly be of interest for readers and potential users of the model products.

Thanks for the comment. Since SST has a very good satellite data coverage, it's not easy to exclude one single mooring from the set of observation assimilated and consider that observation completely independent. This is a typical dilemma while running an operational system. We are trying to assimilate all the available data to improve the quality of our products, but this implies that we reduce significantly the number of independent observations available for the validation. Due to our choice, we don't have a time series for a non -assimilated mooring.

Figure 9. It is quite remarkable the overestimation of the 12-h energy peak in AMM15. Any relation with the harmonic bias in M2? It is also interesting the notorious AAM15 peak around 6-h. Can the authors comment on it? Any explanation? May it be linked to the meteorological forcing? (different in both model systems).

The power spectra shown in Figure 9 is for the FINO 3 buoy (number 2 in Figure 4). The buoy is in the German bight, where the bathymetry is shallow (~20m). The 12h energy peak overestimation is remarkable in SON (wrongly marked as DJF in the manuscript, now corrected), at the end of the summer when probably the two models have different stratifications. The water column is moved by the tides (M2 in the predominant tide) and this could bring to differences in the SST variability. The stratification is this area could also be enhanced by the fresh water contribution of two major rivers, Elbe and Weser. This hypothesis is supported also from the analysis of the map of SST gradients (not shown in the paper) where AMM15 shows stronger gradients than AMM7. Further studies are needed to understand better the SST variability in AMM5.

P23.1 E-Hype. What is E-Hype? No mention to this name in the section where forcing are described. Please, introduce complete name of the source or reference.

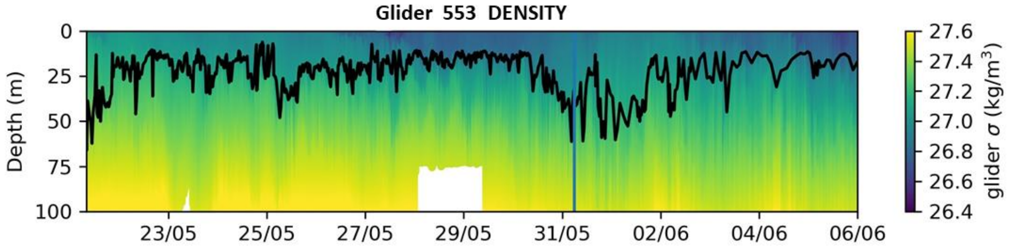
Thanks for the comment. E-Hype is the hydrological model for the European areas developed by the Swedish Meteorological and Hydrological Institute (SMHI)**,** http://hypeweb.smhi.se/explore-water/geographical-domains/#europehype) We have included this information in the manuscript at P23.1 but not in the section where forcing are described because neither AMM15 nor AMM7(in the trial run described in this study) are forced by E-Hype in the experiments described in this study. AMm7 was forced by E-Hype in a version in operation before April 2017.

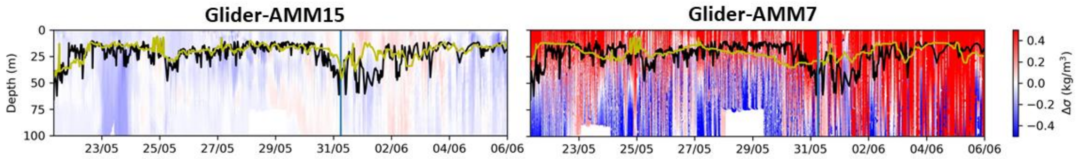
P24.24 Please, check the date: 23rd March or 23rd May (as referred in the Figure 12 caption; in this Fig 13 caption, correct typo: 23rt).

Thanks, done.

In Section 4.4.4 it is discussed about model differences in MLD and it is referred to the Figure 15, where only the MLD computed from the glider is depicted. Why the MLD computed from the models are not shown in the panels Glider-MM15 & Glider-MM7 together with the one derived from the glider data? Include the MLDs from both models in the plot can enhance the analysis in this section dedicated to MLD.

Thanks for the comment, we have added the model MLD to these figures (Yellow line for AMM15 and AMM7 respectively. The black line represents the MLD from the observations).
We added this information in the manuscript, P27.17:
"...with AMM15 and AMM7 in the corresponding locations (yellow line in Figure 15)" and in the caption of the figures.



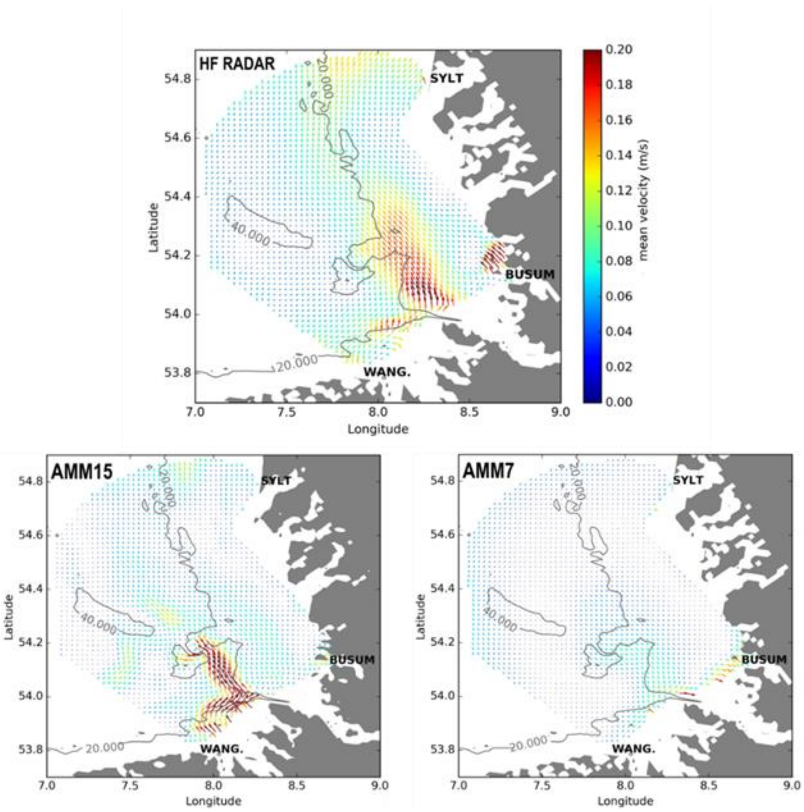


Section 4.5 is devoted to show some results from currents compared with HF-Radar data. As in the previous case for the tides, only a month of data (March 2017) is shown. Please, justify why a so short temporal coverage for the validation.

Please see answer to comment P16.5

Figure 16 shows monthly values of the HF-Radar and from the 2 models, interpolated to the observational field. However, no information on how many observations support the resulting monthly value is provided. Please, include the % of data availability for the month shown. It will be also useful to have some information on the validation of the HF-Radar measurement, as well as on the gap filling methodology used (if someone is used).
The explanation/discussion of the comparative results is quite poor. Please, provide some more description of the features depicted. For instance, it will be interesting that the authors describe the high currents feature existing in front of Wang and Busum stations, reproduced by the AMM15, but not for the AMM7 model. Likewise, any explanation or comment about possible border effects in the HF-Radar field shown would also be pertinent. Can the authors ensure that all the high currents depicted at the border of the HF Radar coverage are reliable? Please, include some info in the text (a reference would also help) on the existing validation of the HF Radar data used and about the possibility of border effects in the observational data used.

Thanks to this comment we realised that we used in the manuscript the map of velocities before the cleaning of data instead of after. The reviewer is right, we can't ensure that the high currents depicted at the border of the HF radar coverage are reliable. We substituted Figure 16 with the corrected Figure.



We have also added the following information in the manuscript:

"The HF radar surface currents were also used to investigate the sub-tidal circulation in the German Bight. The strong tidal signal in the shallow German Bight results in Kelvin waves propagating eastward on the southern boundary along Germany and northward at the eastern boundary along Denmark. However, this cyclonic circulation may not dominate as other processes are also influencing the circulation such as topographic effects from the shallow basin, wind and stratification resulting from freshwater input mostly from the Elbe and Weser river discharge. Wind tends to also produce a residual cyclonic circulation (Schrum 1997, Dick et al 2001, Port et al 2011). During the month of March 2017, a weak cyclonic circulation was observed in the mean HF radar surface currents along the German and Danish coasts (Figure 6). It is also observed in the AMM15 simulations and as a weaker flow in AMM7. The strong flow out of the Elbe estuary is evident in AMM15 currents pattern, even if shifted to the west. AMM7 shows an intensification of its currents in this area, but with a speed much smaller than the observations and AMM15 (Figure 6). Generally…."

Yes, we added the following references:

Dick S, Eckard K, Müller-Navarra S, Klein H, Komo H: The operational circulation model of BSH (BSHcmod)— model description and validation. Berichte des Bundesamtes für Seeschifffahrt und Hydrographie (BSH) 29, BSH, 2001.

Port, A., Gurgel, K. W., Staneva, J., Schulz-Stellenfleth, J., & Stanev, E. V.: Tidal and wind-driven surface currents in the German Bight: HFR observations versus model simulations. Ocean Dynamics, 61(10), 1567-1585, 2011.

Schrum C: Thermohaline stratification and instabilities at tidal mixing fronts. Results of an eddy resolving model for the German Bight. Cont Shelf Res 17(6):689–716, 1997.

The analysis of the AMM7 & AMM15 model currents provided from P 28.14 till the end of the Section 4.5 (including reference to Figure 17) is not referred to any model validation. It is not used any observational data source used as reference. Therefore, I would suggest taking this analysis out from this Validation section. I found the analysis interesting, and it illustrates quite well the dynamical differences existing between both model solutions. If the authors want to keep this analysis in the manuscript, I would suggest moving this part of the text and the figure to the end of the Section 3 (where Trial experiments are described). This analysis of the dynamical patterns obtained gives a good idea of how different the 2 model solutions are and it may give a good introduction to the reader to the validation results that come later in Section 4.

Done, as described at the very beginning of this document.

5.Conclusions

P30.7 typo: temporal

Corrected

Please, include in the conclusion section some reference to the Data Assimilation performed in the AMM15 system, with mention to potential future plans to enhance the assimilation process (and very specially for SLA on the shelf).

Thanks for this comment. We added in the manuscript the following paragraph:

"*The assimilation scheme used in AMM15 is broadly unchanged from that used in AMM7. While the short correlation length-scale is now ~5km (compared to ~20km), the observation and background error covariances, and the observation types assimilated, remain unchanged. In this initial implementation of AMM15 we have not attempted to improve the use of observations in the assimilation scheme. We are currently investigating how to adapt our assimilation scheme to assimilate SLA observations in stratified water and will be re-estimating the observation and background error covariances for this new higher resolution system.*"

P31.18 The AMM15 ocean (system?).

Corrected

The impact of a new high-resolution ocean model on the Met Office North-West European Shelf forecasting system

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Abstract

The North-West European shelf ocean forecasting system has been providing oceanographic products for the European continental shelf seas for more than fifteen years. In that time several different configurations have been implemented, updating the model and the data assimilation components.

The latest configuration to be put in operations, an eddy resolving model at 1.5 km (AMM15), replaces the 7km model (AMM7) that has been used for ~~a number of~~eight years to deliver forecast products to the Copernicus Marine Service and its precursor projects. This has improved the ability to resolve the mesoscale variability in this area. An overview of this new system and its initial validation is provided in this paper, highlighting the differences with the previous version.

Validation of the model with data assimilation is based on the results of two years (2016-2017) trial experiments run with the low and high resolution systems in their operational configuration. The 1.5 km system has been validated against observations and the low resolution system, trying to understand the impact of the high resolution on the quality of the products delivered to the users. Although the number of observations is a limiting factor, especially for the assessment of model variables like currents and salinity, the new system has been proven to be an improvement in resolving fine scale structures and variability and provides more accurate information on the major physical variables, like temperature, salinity and horizontal currents. AMM15 improvements are evident from the validation against high-resolution observations, available in some selected areas of the model domain. However, validation at the basin scale and using daily means penalised the high-resolution system and does not reflect its superior performance. This increment in resolution also improves the capabilities to provide marine information closer to the coast even if the coastal processes are not fully resolved by the model.

1. Introduction

The North-West European Shelf (NWS) is a shallow shelf region consisting of the North Sea, the Irish Sea, the English Channel and the surrounding waters of the Skagerrak, Kattegat in the east and the North and South-West approaches in the west, see Figure 1. These shelf seas are predominantly shallow (with the exception of the Norwegian Trench) and highly tidal. Marine industries in these waters are substantial, with well-established fishing and commercial oil and gas industries more recently being joined by the renewables activities which are continuously expanding. The countries that have coastlines in the NWS are in the main densely populated in these coastal regions and so there are also significant populations that are directly affected by the marine environment in the NWS, with coastal flooding a particular issue due to the high tides, waves and storm surges. The increasing focus on understanding the marine environment in support of sustaining healthy and biologically diverse seas is also a considerable driver in these waters, where human activities like heavy industrial and farming activity, as well as fishing, together with ~~and~~ climate change effects, may have significant impacts on the quality of the marine environment.

There is therefore a significant history of marine monitoring and prediction in support of sustainable use of our marine environment, with the Safety of Life at Sea imperative leading to surface wave models providing forecasts, followed by ocean model forecasts predominantly by the need for storm surge prediction and (more recently) currents and hydrodynamics, in the main led by Defence requirements, but also supporting industry and marine planning (Siddorn et al., 2016). Most recently of all there has been an increasing focus on sustained monitoring and forecasting of the lower trophic ecosystem and marine biogeochemistry (She et al., 2016). The Met Office, with the support of collaborators from around the North-West Shelf region, has for a number of years being producing freely available marine predictions and forecasts for this region as part of the Copernicus Marine Environment Monitoring Service (CMEMS, Le Traon et al, 2017) and precursor projects (e.g. Siddorn et al., 2007; O'Dea et al., 2012).

The operational ocean forecasting systems developed with the Forecasting Ocean Assimilation Models (FOAM) are based on a seamless prediction philosophy whereby the global and regional systems rely on similar ocean modelling and assimilation tools, and are co-developed for short-range forecasting, seasonal forecasting (e.g. MacLachlan et al., 2015, Tinker et al. 2018) and climate predictions (Williams et al, 2018). The operational forecasting configuration for the North-West European Shelf (NWS) is a FOAM system designed to deal with the specific constraints of operational oceanography on a shallow continental shelf sea. The model domain (shown in Figure 1) extends into the Atlantic Ocean to resolve exchanges across the shelf, of primary importance for the continental shelf seas dynamics and water properties. The Atlantic region is chosen to allow the propagation and downscaling onto the shelf of phenomena associated with the large scale open ocean circulation. For example, the North Atlantic Current and European Slope Current which transport heat and salt from the North-East Atlantic, interact with the continental shelf slope and forms branches that flow into the North Sea. The boundaries in the Baltic cover the Kattegat-Skagerrak area, to provide the Baltic inflow, which has a significant influence on the region's water masses due to the significant, and highly variable, freshwater fluxes.

The NWS system has three major components: an ocean model coupled with a biogeochemistry model and a variational data assimilation scheme. This system runs a forecast cycle every day to provide 6-day forecasts of the physical and biogeochemical variables in this area. The forecast is initialized by running two 24-hr analysis cycles. By assimilating observations in this way, the FOAM system incorporates information from considerably more observations than would be available in near-real time with a single 24-hour window, due to the addition of late-arriving observations.

Until recently the operational system for this region has been run at approximately 7 km horizontal resolution (O'Dea et al., 2012; King et al., 2018). This paper describes the operational implementation of the 1.5 km version of this ocean model, referred to as the Atlantic Margin Model, or AMM15 (Graham et al, 2018a). The dominant dynamical scales decrease with reducing water depth and have complex interactions with tidal phenomena and other bathymetric interactions requiring a modelling system at a kilometric scale resolution for this region (Polton, 2015, Holt et al., 2017). The increase of resolution to 1.5 km is therefore a fundamental step change in the ability to resolve key processes and features in the NWS region (Guihou et al., 2017). As well as being developed for ocean forecasting operations, the AMM15 is being used within a coupled ocean-wave-atmosphere research system (Lewis et al., 2018a and 2018b).

The upgrade of the NWS system to AMM15 does not yet include the biogeochemical component as the computational cost is prohibitive, with the production time exceeding the 24-hr for a full hindcast-forecast cycle. Two systems are therefore being run in parallel: i) the 7 km AMM7 model with the physical and biogeochemical components similar to O'Dea et al.

(2012) and ii) a 1.5 km AMM15 physics only system (being detailed~~scribed~~ in this paper), as described by Figure 2.~~.~~ An AMM15 based coupled physics-biogeochemistry model is under development, and techniques are being developed to reduce the computational cost to allow it to be implemented within the time constraints of operational production. Herein, therefore we describe only the physical component of the high-resolution (AMM15) system, highlighting the differences with the low resolution configuration (AMM7). O'Dea et al. (2017, 2012) provide full descriptions of the AMM7 version of this system. It is worth noting here that the NWS system also has a wave component providing products on the same grid as the AMM15 (Figure 2).~~.~~ The wave and physical models are forced by the same wind fields and the wave model uses the surface currents computed by AMM15. However, the wave model description and validation are not within the scope of this paper.

The7km products (AMM7) delivered through Copernicus are:

- NORTHWESTSHELF_ANALYSIS_FORECAST_PHYS_004_001_b (http://marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-001.pdf);
- NORTHWESTSHELF_ANALYSIS_FORECAST_BIO_004_002_b (http://marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-002.pdf).

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The1.5km products (AMM15) delivered though Copernicus are:

- NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_013 (http://marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-013.pdf);
- NORTHWESTSHELF_ANALYSIS_FORECAST_WAV_004_014 (http://marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-014.pdf).

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This study is focused on the product NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_013 and its inter-comparison with NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_001b.

Here we provide details on the AMM15 hydrodynamic model, the data assimilation scheme, and the operational suite in the following section. Section 3 will then describe the trial experiments while Section 4 details our assessment of the new high-resolution products. Our conclusions are presented in Section 5.

2. System Description

2.1 Core Model Description

The Forecasting Ocean Assimilation Model (FOAM) 1.5 km Atlantic Margin model (AMM15) is a hydrodynamic model, one-way nested within the Met Office operational North Atlantic 1/12° deep ocean model (Storkey et al. 2010) and the ~~Copernicus~~ CMEMS operational Baltic Sea model (Berg et al. 2012.). The model core is based on version 3.6 of the Nucleus for European Modelling for the Ocean (NEMO, Madec 2016). This is a community ocean modelling system that has a wide user and developer base, particularly in Europe.

The regional model is located on the North-West European continental Shelf (NWS), extending from approximately 45°N to 63°N, and from 20°W to 11°E. There is a uniform grid spacing of ~1.5 km throughout, in both the zonal and meridional direction (Graham et al. 2018a). The vertical coordinate system is based on a hybrid s-sigma terrain following system, $z^* - \sigma$ (Siddorn and Furner, 2013), with 51 vertical levels. This is the same as that used in AMM7, with the thickness of the surface cell set to ≤ 1 m to guarantee uniform surface heat fluxes across the domain. The terrain-following coordinates used here are fitted to a smooth envelope bathymetry, where the level of smoothing is determined such that the local bathymetric slope $r = (h_i - h_{i+1})/(h_i + h_{i+1})$, computed between adjacent bathymetry points h_i and h_{i+1}, is constrained to be less than a specified maximum value (r_{max}). This is required to mitigate against spurious horizontal velocities that arise from horizontal pressure gradient errors in terrain following coordinates that are too steep. Although the number of levels in both AMM15 and

AMM7 are the same, the steeper gradients resolved in AMM15 means that a lower r_{max} value was chosen (0.1, compared to 0.24) to ensure stability along the shelf-break.

The bathymetry chosen for AMM15 (and shown in Figure 1 and summarized in Table 1) is from the European Marine Observation and Data Network (EMODnet Portal, September 2015 release). The increased resolution of both AMM15 and this EMODnet data set allows for improved representation of fine-scale features and processes, particularly along the shelf-break. The original EMODnet data is referenced to Lowest Astronomical Tide (LAT), so has been converted to M~~m~~ean S~~s~~ea L~~l~~evel (MSL) for use in the model. The differences between LAT and MSL referenced bathymetry are negligible in the deep ocean, but can be large on shelf, particularly in shallow coastal areas with large tidal ranges. The model minimum depth is forced to be 10m, ~~-~~due to the tidal limit and lack of wetting and dry. This choice ensures that no locations dry out, due to the tides. Further details on the model domain and bathymetry can be found in Graham et al. (2018a).

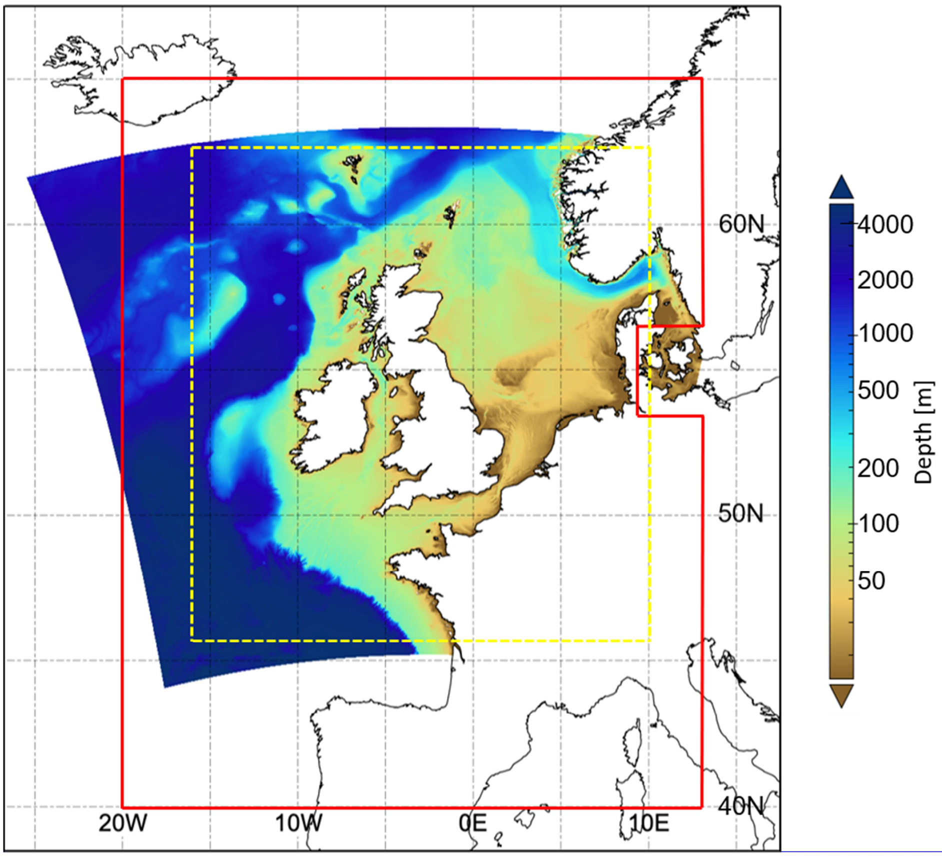
Tidal modelling requires a non-linear free surface and this is facilitated in NEMO by using a variable volume layer method. The short time scales associated with tidal propagation and the free surface require a time splitting approach, splitting modes into barotropic and baroclinic components. The model uses a non-linear free surface, an energy and enstrophy conserving form of the momentum advection, and a free slip lateral momentum boundary condition. The tracer equation's use a TVD (Total Variance Diminishing) advection scheme (Zalesak, 1979).

Table 1: Summary of the AMM15 –AMM7 model differences.

Model differences	AMM7	AMM15
Geographical domain	40°N- 65°N 20°W – 13°E Regular grid	~ 45°N - 63°N ~ 20°W - 13°E The grid has a rotated pole, chosen so that the *grid-equator* runs through the domain to reduce the distortion of cells with increasing latitude. While the rotated latitude is constant, the longitudinal grid steps range from ~1.47 km to 1.5 km.
Bathymetry	GEBCO corrected by NOOS partners	EMODnet 2015
Horizontal resolution	7km	1.5km
Timestep	300s (10s barotropic sub-timestep)	60 s (~3.5s barotropic sub-timestep)
Penetrative radiation	1-band shortwave radiation light attenuation (as used in POLCOMS, Holt and James 2001)	NEMO tri-band Red-Blue-Green (RGB)
Bottom friction	Log layer. Minimum drag coefficient 1.0 x 10^{-3}	Log layer. Minimum drag coefficient 2.5 x 10^{-3}
Momentum diffusion	bi-Laplacian on model levels 1×10^{10} m^4/s	bi-Laplacian on model levels 6×10^7 m^4/s
Tracer diffusion	Laplacian on geopoential levels 50 m^2/s.	bi-Laplacian on model levels 1×10^5 m^4/s

Since both AMM15 and AMM7 have a similar vertical grid, the vertical parameterizations remain similar. The generic length-scale scheme is used to calculate turbulent viscosities and diffusivities (Umlauf & Burchard, 2003). Dissipation under stable stratification is limited using the Galperin limit of 0.267 (Holt & Umlauf, 2008). Bottom friction is controlled through a nonlinear log layer, with a minimum drag coefficient of 2.5×10^{-3} (compared with a coefficient of 1.0×10^{-3} in AMM7), as described in Table 1.

As many more fine-scale mixing processes are resolved in AMM15, only minimal eddy viscosity is applied in the lateral diffusion scheme. For momentum and tracers, bi-Laplacian viscosity is applied on model levels with coefficients of 6×10^7 and 1×10^5 m^4/s, respectively. For AMM7, additional viscosity and eddy diffusivity must be parameterized. A bi-Laplacian scheme is used on model levels for momentum, with a coefficient of 1×10^{10} m^4/s. For tracer diffusion, a Laplacian diffusion scheme is used on geopotential surfaces, with a coefficient of 50 m^2/s (Table 1).



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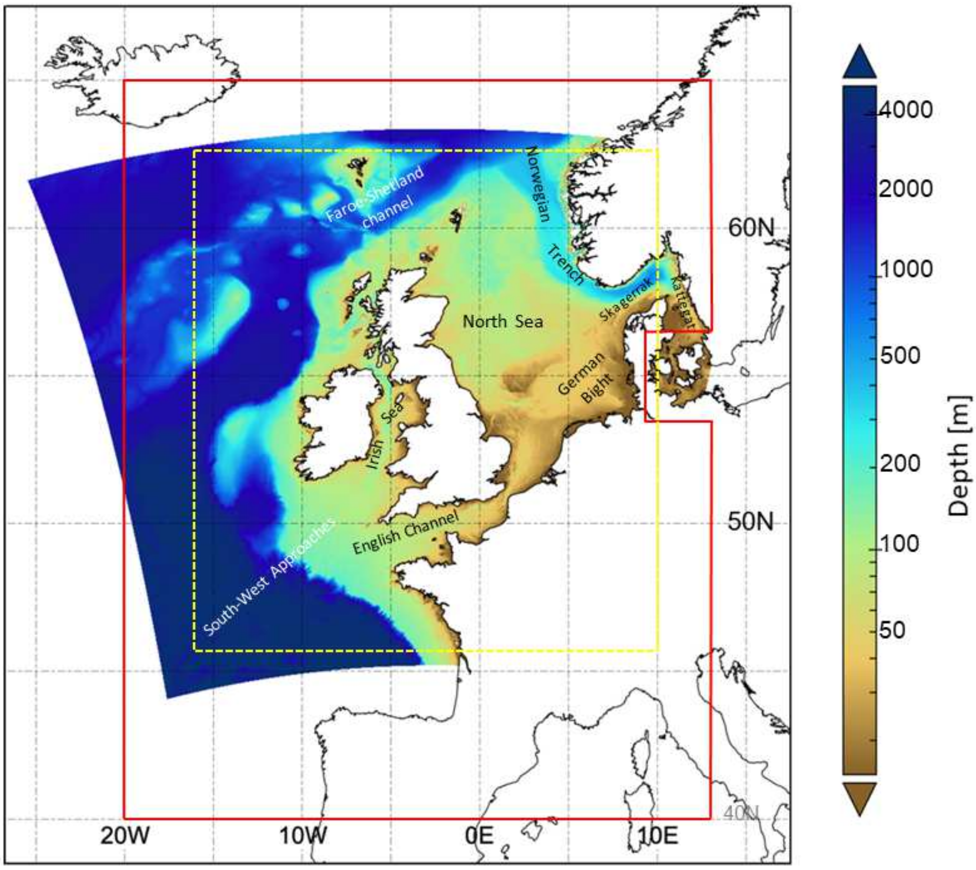

Figure 1: EMODnet bathymetry, in meters (logarithmic scale), showing the NWS high resolution, AMM15, model domain. The red line defines the NWS low resolution, AMM7, model domain. The yellow dotted box is the domain covered by the AMM15 products delivered on a regular grid to the Copernicus users. Figure modified from Graham et al. (2018). The bathymetry colour range has logarithmic scale.

2.1.1 Boundary and s~~S~~urface f~~F~~orcing

Tidal forcing is included both on the open boundary conditions via a Flather radiation boundary conditions (Flather, 1976) and through the inclusion of equilibrium tide. The Topex Poseidon cross-over solution (Egbert and Erofeeva, 2002; TPX07.2, Atlantic Ocean 2011-ATLAS) provides 11~~2~~ constituents for amplitude and phase of surface height and velocity at 1/12°.

The model is one-way nested with the Met Office Operational North Atlantic 1/12° deep ocean model (Storkey et al., 2010) and the ~~Copernicus~~ CMEMS operational Baltic Sea model (Berg et al., 2012). They provide temperature, salinity, sea surface height (not at the Baltic boundary), and depth integrated currents at the open boundaries. The two models, AMM7 and AMM15, are both nested in the open Atlantic and Baltic boundaries to the same products, but the boundaries are in a different geographical position due to the different model domains.

AMM7 and AMM15 are forced at the air-sea interface by two different Numerical Weather Prediction (NWP) outputs, the Met Office Unified Model (MetUM) global atmospheric model for AMM7 and the European Centre for Medium-Range

Weather Forecasts (ECMWF) operational Integrated Forecasting System (IFS) for AMM15, see Table 2 for details. The Copernicus Marine Environment Monitoring Service requested the change from the MetUM to IFS forcing with the aim of minimizing differences among the regional systems covering all the European seas. The fields from ECMWF and Met Office have a similar spatial resolution but IFS fields for wind and atmospheric pressure have a lower temporal resolution as described in Table 2. The IFS analysis is available only at a low temporal resolution (6 hours) therefore the decision was made to force the system using forecast fields only (3 hourly), from the 00:00 UTC forecast base time run. A specific set of experiments are needed to assess the impact of this choice but are not within the scope of this paper. ECMWF products at higher temporal resolution are now available and will be used in future releases of this operational system, improving the atmospheric forcing of this first version of AMM15. The IFS forcing is applied using the CORE (Common Ocean-ice Reference Experiment) bulk formulae (Large and Yeager, 2009). The specific humidity, sH, not available from the IFS field, is computed from the dew point temperature at 2m and the surface pressure using the World Meteorological Organization formulation (WMO, 2010):

$$sH = \frac{mwa * 100 * rSP * 10^2}{SP - (1.0 - mwa) * 100 * rSP * 10^2}$$

Where *mwa* is the ratio between the molecular weight of water and of dry air; *rSP* is the reference surface pressure; *SP* the surface pressure. The AMM7 instead is forced at the surface by direct fluxes from MetUM and using the COARE4 bulk formulae, as described in O'Dea et al. 2012.

An atmospheric pressure gradient force is applied at the surface of both models, using the atmospheric pressure field from MetUM and IFS respectively which affects the model free surface elevation.

The light attenuation in AMM15 is set to the standard NEMO tri-band scheme (RGB), assuming a constant Chlorophyll concentration (Graham et al. 2018a). AMM7 uses the single band light scheme previously used in the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS) and outlined in Holt and James (2001). In this single band light scheme, the extinction depths vary across the domain in proportion to the bathymetry in order to estimate the change in water clarity between deep and shallow waters.

For AMM15, river run-off is based predominantly on a daily climatology of gauge data averaged for 1980–2014. UK data were 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 Sonja M. van Leeuwen, CEFAS, Lowestoft, UK, personal communication, 2016). For major rivers that were missing from this data set (e.g. along the French and Norwegian coast), data have been provided from an earlier climatology (Young and Holt, 2007; Vorosmarty et al., 1998), based on a daily climatology of gauge data averaged for the period 1950-2005, which is the climatology used by AMM7. The differences between AMM15 and AMM7 river discharge data are expected to be mainly, but not only, along the UK coastline.

Table 2: AMM7 and AMM15 forcing description.

Forcing	AMM7	AMM15
Surface forcing	Met Office Global Unified Model (MetUM) Atmospheric model NWP analysis and forecast fields, calculated in the MetUM using COARE4 bulk formulae (Fairall et al. 2003).	ECMWF Integrated Forecasting System (IFS)-Atmospheric Model High Resolution (HRES) operational NWP forecast fields using CORE bulk formulae (Large and Yeager 2009)

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Surface forcing resolution	Horizontal grid: ~10 km (2560 x 1920 grid points) Frequency: 3 hourly mean fluxes of long and short wave radiation, moisture, 3 hourly mean air surface temperature but hourly 10m winds and surface pressure	Horizontal grid: ~14 km (0.125°x0.125°). Frequency: 3 hourly instantaneous 2m dew point temperature, surface pressure, mean sea level pressure, and 2m air temperature. 3 hourly accumulated surface thermal and solar radiation, total precipitation, and total snow fall.
River run-off	Daily climatology of gauge data averaged for 1950–2005. Climatology of daily discharge data for 279 rivers from the Global River Discharge Data Base (Vörösmarty et al., 2000) and from data prepared by the Centre for Ecology and Hydrology as used by (Young and Holt, 2007).	Daily climatology of gauge data averaged for 1980–2014. UK data were processed from raw data provided by the Environment Agency, the Scottish Environment Protection Agency, the Rivers Agency (Norther Ireland), and the National River Flow Archive (personal communication by Sonja M. van Leeuwen, CEFAS, 2016). For major rivers that were missing from this data set (e.g. along the French and Norwegian coast), data have been provided by the same climatology used by AMM7 (Vörösmarty et al., 2000 and Young and Holt, 2007).
Tidal constituents	M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, L2, T2, S1, 2N2, MU2, NU2 (15) from a tidal model of the North-East Atlantic (Flather, 1981).	M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, MN4 (11) from Topex Poseidon cross-over solution (Egbert and Erofeeva, 2002; TPX07.2, Atlantic Ocean 2011-ATLAS).
Lateral boundaries	Met Office FOAM North Atlantic (1/12°; 6 hourly fields) and CMEMS Baltic Sea (2km, 1 hourly fields).	
	AMM7 and AMM15 have Atlantic and Baltic boundaries in a different geographical location.	

2.2 Assimilation method

The data assimilation component of FOAM is NEMOVAR, a multivariate, multi-length scale assimilation scheme developed collaboratively by the Met Office, the Centre Europeen de Recherce et de formation avancee en calcul scientifique, the ECWMF, and the Institut National de Recherche en Informatique et en Automatique (Mogensen et al., 2012). This has been implemented at the Met Office as an incremental 3D-Var, first guess at appropriate time (FGAT) scheme for the 1/4° global model (Waters et al., 2015) and the 7 km Atlantic Margin Model (AMM7, King et al. 2018).

An assimilation window of 24-hours is used, and observations assimilated include in situ and satellite swath SST observations, altimeter measurements of SLA (in regions with depth>700 m), and profile observations of the sub-surface temperature and salinity from a number of sources as detailed in Table 3 ~~Table 4~~. The SLA observations assimilated in this model are provided through CMEMS and include the corrections necessary to add back the signals due to tides and wind and pressure effects necessary for use with a wind and pressure forced, tidal coastal model (king et al., 2018). ~~. Increments are~~

~~applied to the model fields at each time-step using the incremental analysis update procedure (IAU,~~ After the assimilation step, the model is re-run for the same period with a fraction of the increments applied to the model fields at each time step (the Incremental Analysis Update procedure (Bloom et al. 1996).

The Met Office implementation of NEMOVAR includes bias correction scheme for both SST and altimeter data. The SST bias correction aims to correct for biases in the observed SST due to the synoptic scale atmospheric errors in the satellite retrievals, while for SLA we apply a slowly-evolving bias correction to correct for errors in the MDT ~~This Met Office implementation of NEMOVAR includes bias correction schemes for both SST and altimeter data~~ (Lea et al. 2008).

In the AMM15 implementation described here the assimilation component has been upgraded to NEMOVARv4, which introduced a small number of changes compared to the scheme used in AMM7 (detailed in Table 4 ~~Table 3~~). In the AMM7 configuration, which uses NEMOVARv3, the SST bias correction scheme employs observations-of-bias (determined by matching nearby, contemporaneous in situ and satellite observations) to estimate a daily correction to the observations from each SST satellite. In NEMOVARv4 a variational bias correction has been introduced which combines information from average SST innovations with the observations-of-bias used previously. We have also included observations from VIIRS in our reference dataset against which the other satellite SST observations are bias-corrected. This new scheme has been shown to be more resilient to changes in the observing system and gaps in observation coverage (While & Martin 2018). The SLA bias correction in AMM15 is unchanged from AMM7.

Although the same observation and background error variances are used in AMM15 as in AMM7 (see King et al. 2018), the background error correlation length-scales have been modified. The spatial covariance of background errors is modelled using an implicit diffusion operator with the horizontal length-scales specified a priori, and the vertical length-scales specified using a parameterisation based on the mixed-layer depth. In NEMOVARv3 this was modelled using three 1D diffusion operators, but in NEMOVARv4 it is modelled using a 2D horizontal diffusion with a 1D vertical diffusion (Weaver et al. 2016). In both systems, two horizontal correlation length-scales are used (Mirouze et al., 2016): 100km for the long length-scale and the Rossby radius of deformation for the short length-scale. To avoid numerical computation issues, the short length-scale is restricted to have a minimum value equivalent to 3-times the grid-scale. This has the result that in shallow water the short length-scale for AMM15 can be as small as 4.5 km compared to 21 km for AMM7.

Table 3: List of observations used for data assimilation.

Type	Fields	Platforms/Satellite	Data source/Product
IN SITU	SST Temperature and salinity profiles	• Ships • Drifters • Fixed moored arrays • Gliders • XBTs • CTDs • ARGO • Ferry boxes • Recopesca buoys* • Thermosalinograph	GTS; http://www.wmo.int/pages/prog/www/TEM/GTS ~~CMEMS INS TAC~~ http://marine.copernicus.eu/ INSITU_GLO_NRT_OBSERVATIONS_013_030

SATELLITE	SLA Along Track* **along with the corrections necessary for the use with a wind and pressure forced, tidal coastal model. SLA are assimilated only in deep regions (> 700m).*	• Cryosat-2 • Altika • Jason 3 • Sentinel 3a	~~CMEMS SL TAC:~~ http://marine.copernicus.eu/ SEALEVEL_EUR_PHY_ASSIM_L3_NRT_OBSERVATIONS_008_043
	SST L2p/L3c	• NOAA-AVHRR • MetOp-AVHRR • SEVIRI • VIIRSG • AMSR2	Group for High-Resolution Sea Surface Temperature (GHRSST) www.ghrsst.org

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Table 4: AMM15-AMM7 differences in the data assimilation scheme

Data Assimilation	AMM7	AMM15
NEMOVAR version	V3	V4
SST bias correction scheme:	Offline observations-of-bias scheme. Reference dataset: in-situ.	Variational scheme in addition to observations-of-bias. Reference datasets: in-situ (drifters only) and VIIRS satellite data.
Correlation operator short scale: 3-times grid scale	~20 km	~5 km
Mean Dynamic Topography	CNES-CL09 mean dynamic topography (MDT, Rio et al. 2011)	

2.3 Operational production

The FOAM system produces daily 2-day analyses (Best Estimate and NRT analysis) and a 6-day forecast (Figure 2). The timeliness of the observations, in situ and from satellite, significantly affects the number and the quality of the observations available in the 24 hrs preceding the forecast, so two analysis cycles of 24 hr each are run to include as many observations as possible in the data assimilation.

The observations are downloaded from different sources: ~~Copernicus Marine Environment Monitoring Service (~~CMEMS~~)~~ for Sea Level Anomaly L3 products, Group for High Resolution Sea Surface Temperature for the L2 SST satellite observations and the Global Telecommunication System (GTS) and CMEMS for the in-situ observations. The vertical profiles need to be thinned to reduce the spatial error correlation between the observations. For a given 24 hours, they are thinned in 3D space with the values: Δlon, Δlat=0.2°, Δz=10m. Prior to data assimilation, a quality check of the observation is performed using the model background produced by the forecast cycle of the previous day (Ingleby et al., 2007). Observations flagged as bad are not used for the data assimilation. The quality check for the vertical profiles is performed at 51 geopotential standard depth. The full profile is rejected only if more than 1/~~3~~ 2 is flagged as bad. The QC information, the background and observations fields are stored in specific files, known as feedback files. The error thresholds for the QC are set in order to avoid unrealistic model fields due to bad observations.

The lateral boundaries for the Atlantic region and the Baltic are both from the forecast production of the previous day. The Baltic boundaries are downloaded every morning a few hours before starting the operational suite for the NWS. The CMEMS Baltic Sea product has 5-day forecast, produced twice a day, at 00:00 and at 12:00 and delivered at 07:00 and 19:00 UTC respectively. The NWS models are forced with the latest data available at 05:00 UTC and the last hourly field is persisted to produce the last day of forecast.

The atmospheric forcing is downloaded from ECMWF and since the last set of data is available at 07:00 UTC, production is started 15 minutes later to allow for download delays. Once the model and data assimilation task are over, the post-processing task starts because the products need to be organized for delivery to the users. The raw output files are interpolated on a standard grid at the same resolution as the model rotated grid, 1.5 km, but covering a slightly smaller area (see the yellow rectangular dotter line in Figure 1). The vertical terrain-following levels are converted for users' convenience, into 33 standard geopotential levels: [~~0~~surface, 3, 5, 10, 15, 20, 25, 30, 40, 50, 60, 75, 100, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, 550, 600, 750, 1000, 1500, 2000, 3000, 4000, 5000 m]. All the files are then packaged to be compliant with the CMEMS~~opernicus~~ and CF standards. Each day the best estimate [T-48h, T-24h] and NRT [T-24h, T+00h] analyses are delivered as well as 6 forecast days for all products (with the first day of the forecast being for the day of production). The delivered products are 25 hr daily means and hourly instantaneous products of temperature, salinity, horizontal currents, Sea Surface Height (SSH), Mixed Layer Depth (MLD). Daily mean values are calculated as means of 25 ~~instantaneous~~ hours~~ly values~~, starting at midnight and finishing on the following midnight to remove the tidal cycles. The data are in netCDF4 format and the volume of each production cycle is ~14 Gb (1.7Gb for each day), while for AMM7 is ~1Gb.

AMM15 is running on the Met Office HPC – Cray XC40 super computer using 48 nodes and 1536 processors. AMM7 instead is using only 8 nodes and 256 processors. This information is summarized in the Table 5, for each component of the system. :

Table 5: AMM7 and AMM15 computational resources on the Met Office HPC-CrayXC40

System	Component	# of nodes	# of processors
AMM7	NEMO	8	256
	NEMOVAR	2	64
AMM15	NEMO	48	1536
	NEMOVAR	48	1536
	XIOS	8	256

XIOS is for the I/O of NEMO. The small size of AMM7 model grid doesn't require dedicated nodes for this task.

The production process takes approximately 4 hours, four times that required by AMM7. It is planned to improve the robustness of this first implementation of the system by improving the dependencies of the different tasks in the operational suite and investigating ways of reducing the dependency on IFS delivery. The quality of the products and the observations used for the production are monitored each day to allow the ocean forecasting scientists to take action if there are anomalies in the production or missing observations, and to allow users to be promptly alerted in the case of degradation of the products.

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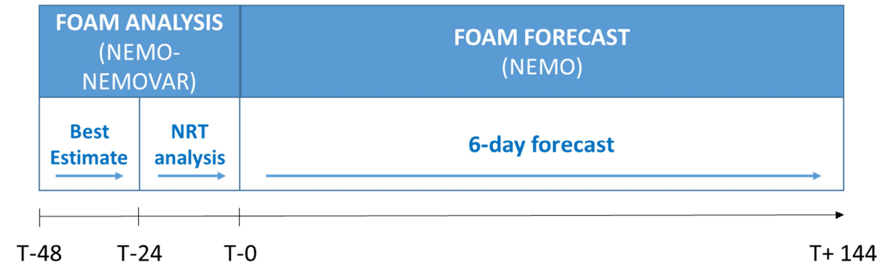

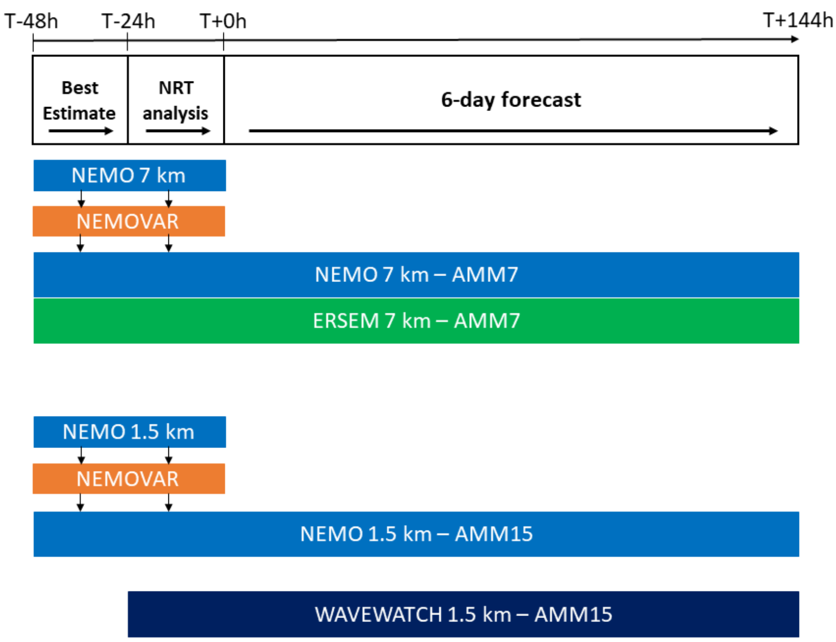

Figure 2: FOAM daily production cycle. The 7km system, top panel, has an ocean model coupled with a biogeochemical model and a variational assimilation scheme. The 1.5 km system, bottom panel, has an ocean model with a variational assimilation scheme and a wave model, forced by the ocean model surface currents (not coupled).

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3. Trial experiments

The assessment of the pre-operational implementation is based on trial experiments covering the years 2016-2017 (Table 6). The strategy for trialling forecasting systems prior to entering into operations is one of significant debate at the time of writing. Ideally, given the relatively poor in situ observational coverage, a long period of trialling would be used to assess the system performance to gain a full (and statistically significant) understanding of its performance in all seasons and under a range of conditions. However, a combination of the length of time and computational cost to run those trials, the overhead in preparing observations and fluxes and the difficulty in finding a period of observations and fluxes that truly reflect the operational conditions, lead to a more pragmatic approach being taken. It should be noted that the AMM15 modelling system itself has already been assessed for a long period and its quality documented in Graham et al., 2018a. Similarly, the data assimilation methodologies are well-tested (King et al., 2018) and have been robust in operations in other implementations. This assessment is therefore complementary and allows an assessment of the system as it is in operations, with fluxes, boundaries and assimilated observations used that are similar to the operational system. The trial experiments are required to cover a period in the recent past in order to avoid differences in the observational network and/or in the forcing resolution/quality. The two years chosen are therefore a balance between covering a multi-year period, that is recent in time (and hence representative of the operational conditions) and achievable on the timescales required to transition into operations.

Before adding a new product to the operational production, the system must be shown to offer an improvement over the previous system. For AMM15 this was done by setting up comparative trials running the existing and the new system, which are running with different forcing and initial conditions. This assures that we reproduce the operational products, new and old, and we validate the quality of the products.
The operational version of AMM7 was re-run rather than using the operational products produced in real time in order to avoid inconsistency in the number and type of observations assimilated by the two systems. Indeed, the real time production can suffer temporary delays or problems in the delivery of the observations that are not reproducible in delayed time.

A free (non-assimilative) run was performed as a control, for both AMM7 and AMM15, but the results are not described in this work, since our aim is to assess the quality of the products delivered to the users. Apart from the resolution, the major differences between AMM7 and AMM15 are in the initial conditions, the atmospheric forcing and the location of the lateral boundaries.

The AMM7 initial conditions are from the operational (assimilating) system while for AMM15 they are from an extension of the non-assimilating experiments presented in Graham et al. (2018a), which finished at the end of 2014. This run was extended to include 2015 and was run with the same source of atmospheric forcing and Atlantic lateral boundary used for 2016-2017. However, the CMEMS~~opernicus~~ Baltic datasets used to calculate the boundaries used in operations for AMM7 are no longer available due to the CMEMS~~opernicus~~ retention policy, and so cannot be used to calculate the AMM15 equivalents. We therefore used the CMEMS~~opernicus~~ product where it was available (for the years 2016 and 2017) but for 2015 a General Estuary Transport Model (GETM, Burchard et al. 2002) implementation for the Baltic (as used by Graham et al. 2018a) was used in its place.

This paper details the assessment of the quality of the AMM15 operational system based on the assimilative run and is therefore representative of the analysis day. Graham et al. 2018a have demonstrated that the AMM15 without data assimilation performs equally or better than AMM7. A detailed assessment of the forecast based on the real time forecast produced since the beginning of November 2018 will be conducted in the future. It is anticipated that the forecast quality improvement for the AMM15 against the AMM7 will be greater than the improvement for the analysis day, given the improved underlying model, but that must still be demonstrated.

Table 665: Summary of the trial experiments.

System Name	Data Assimilated	Initial state	Forcing
AMM7	3D SST, SLA, Sub-surface profiles	restart from AMM7 (assimilative) operational	direct fluxes- MetUM
AMM15	as above for the AMM7	restart from an extension of Graham et al., (2018a) non-assimilating	bulk - IFS

The results and validation of these trials are used for two purposes: as a basis for making a decision on whether to proceed with the operational implementation, and to provide feedback to the researchers developing the models and data assimilation systems to prioritize their research activities.

The observations assimilated in the NWS system are SST from in situ and satellite; SLA from satellite; and sub-surface vertical profiles, as detailed in Table 3 ~~Table 4~~. The satellite measurements guarantee a good coverage of the area, especially for SST, while the sub-surface profiles are variable in terms of number of observations and spatial/geographical distribution. Figure 5~~Figure 4~~~~Figure 3~~ shows the observations distribution during year 2016-2017 for sub-surface observations of temperature and salinity for the two most extreme seasons in terms of data distribution, winter (defined as December-January-February) and summer (June-July-August). In summer 2016 and 2017, there are very few observations on shelf, in particular in the North Sea and this has an impact on the quality of the assimilative runs. Compared to the trial experiments, done in delayed-time, the real-time analysis can have a temporary decrease of quality due to timeliness issues affecting the real-time delivery of observations or poor quality-controlled data.

3.1 System performance: AMM15 vs. AMM7

The impact of the high resolution can be qualitatively assessed comparing models surface currents maps. The current field of AMM15 is more detailed and seems more realistic than AMM7 but the lack of the observations makes it difficult to properly assess the horizontal velocity field in key areas. ~~Figure 17~~Figure 4~~Figure 3~~ represents the surface currents from AMM7 and AMM15 for a single day, to give an example of difference between the two models. AMM15 has a more complex current circulation in the deep part of shelf, with meanders and eddies, not resolved by AMM7. The European slope current, green arrow in Figure 4~~Figure 3~~~~Figure 17~~, is transporting Atlantic water into the North Sea, mainly through the Faroe-Shetland Channel (Marsh at al. 2017), influencing the characteristic of the water in the Northern North Sea and its circulation. The AMM15 current patterns seems more realistic, reproducing eddies and meanders, has shown by drifters measurements done in this area (Burrows et al. 1999). The European slope current plays a major role in the across shelf transport, with AMM15 better reproducing the water exchanges as described in Graham et al 20018b.

The two models are also very different in the area characterised by the Norwegian Coastal Current (NCC) which is highlighted by the yellow vectors in Figure 4~~Figure 3~~~~Figure 17~~.

The NCC is a coastal current flowing from Skagerrak to the Barents Sea, following the Norwegian coastline, in the upper layer (50-100m) over the Norwegian Trench. This current is characterized by a front between low salinity water coming from the brackish Baltic sea and Norwegian coastal water, and the Atlantic water. This current has mesoscale meanders and eddies (Ikeda et al. 1989) propagating northward along the Norwegian coast. AMM15 reproduces better the mesoscale eddies and meanders of the NCC which are not resolved by AMM7.

The Scottish coastal current, seems to be well resolved by AMM15, with a strong current flowing along the west Scottish coast and meandering before entering the channel between mainland Scotland and the Hebrides (the Minch). This is a persistent current that interacts with the island chain of the Hebrides (Simpson 1986). AMM15 has a more detailed coastline and bathymetry in this area which is likely to be one of the main reasons why the model resolves this current. In AMM7, this current is almost absent, or too weak and misplaced to the west, instead of being, as it in AMM15, between the islands and the mainland (~~Figure 17~~, red arrows). The contrast between the low salinity along the coast and the higher salinity of the Atlantic water is another key driver of this current (Simpson 1986), and this is better represented by AMM15, which has an improved salinity field compared to AMM7 (see Section 4). AMM15 seems to be much less diffusive in the proximity of the river plumes keeping a narrower plume close to the coast and has a lower lateral diffusion (Graham et al. 2018a). AMM7 has

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low salinity water (less than 34.5 PSU) spreading much further away from the coast, all the way to the Outer Hebrides, while the salinity gradient in AMM15 is located between the Minch and the western side of the Outer Hebrides. This assessment shows that AMM15 is in very good agreement with literature in this area. Further studies, and possibly targeted observations, are needed to validate this preliminary result and to assess AMM15 skills in predicting the seasonal variability of this current and the other currents described in this study.

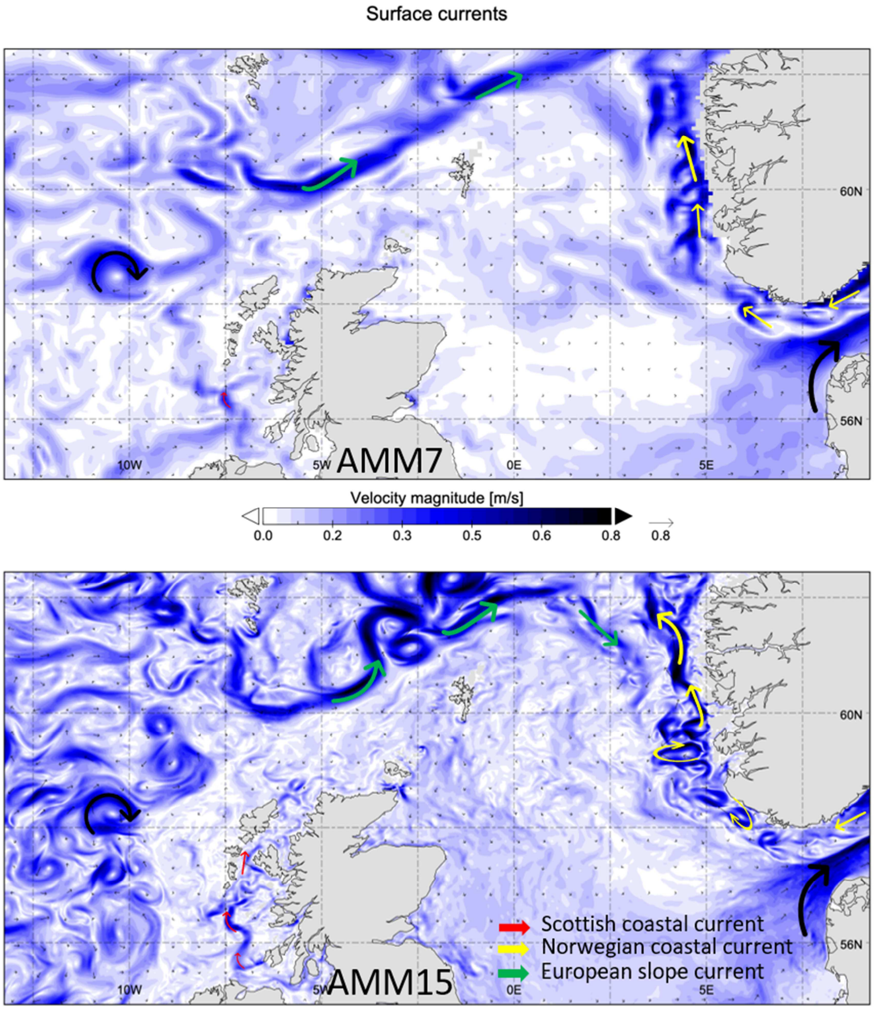
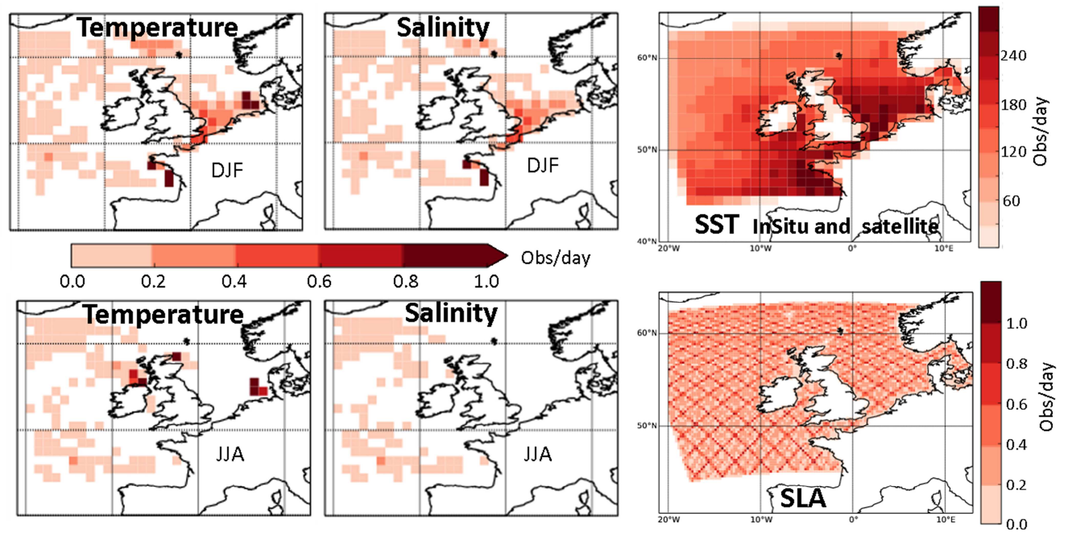


Figure 3~~17~~: Surface current from AMM7 (top) and AMM15 (bottom), daily mean 02-12-2018.



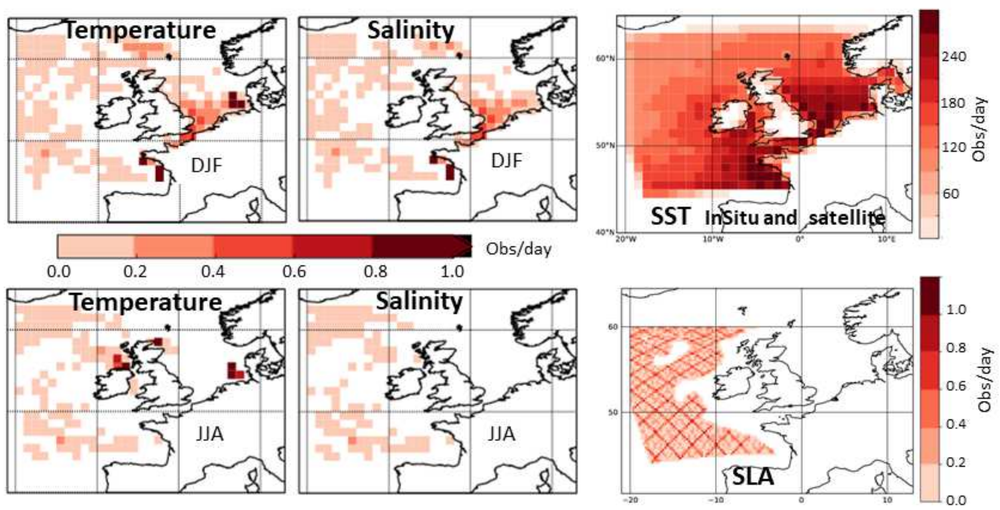


Figure 4~~3~~: Number of observations per day for various observation types over 2016/17: winter (DJF) temperature (top left) and salinity (top middle) profiles in 2-degree bins, summer (JJA) temperature (bottom left) and salinity (bottom middle) profiles, in situ and satellite SST (top right), and satellite SLA (bottom right).

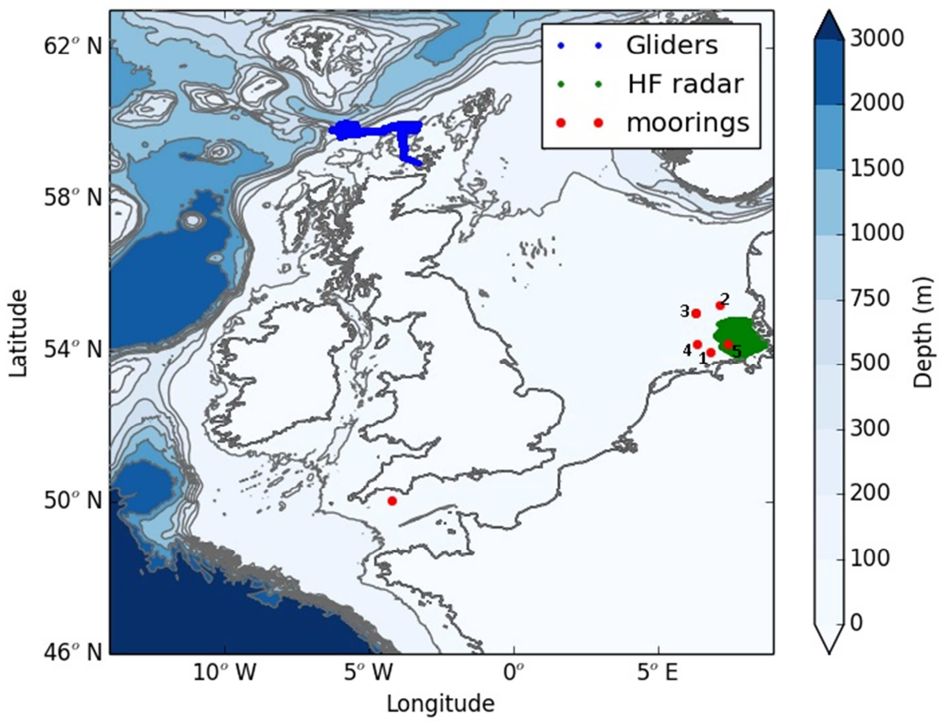
4 Validation of the experiments

Most of the observations used for the global validation are the same as used for the data assimilation, as described in the previous section. The model/observation differences are calculated before the model is corrected by the assimilation, but even so the observations are not fully independent from previously assimilated observations. All the same, this method is commonly used for model validation (King et al. 2018) and we consider the validation significant. Independent observations, available on a very limited geographical domain and/or for a shorter period than the two years, have also been used, and have the benefit of providing an understanding of the impact of the high resolution locally on small areas and short timescales. This approach differs from the validation described in Graham et al. 2018a, which focussed on the seasonal, interannual and multi-year time scales.

The independent observations we have used are:

- Glider transects from the UK MASSMO4 experiments (north of Scotland);
- COSYNA HF radar in the German Bight
- Tide gauges
- Moorings in the German Bight and in the English Channel.

The geographical location of these observations is presented in Figure 5~~Figure 4~~ where each type of observation is marked by a different colour. Also used was the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) L4 SST product (Donlon, et al., 2012) which, although not assimilated, is not fully independent as it assimilates a similar (but not identical) set of SST observations as the AMM7 and AMM15 using similar methods (including using the same assimilation framework, albeit set up slightly differently).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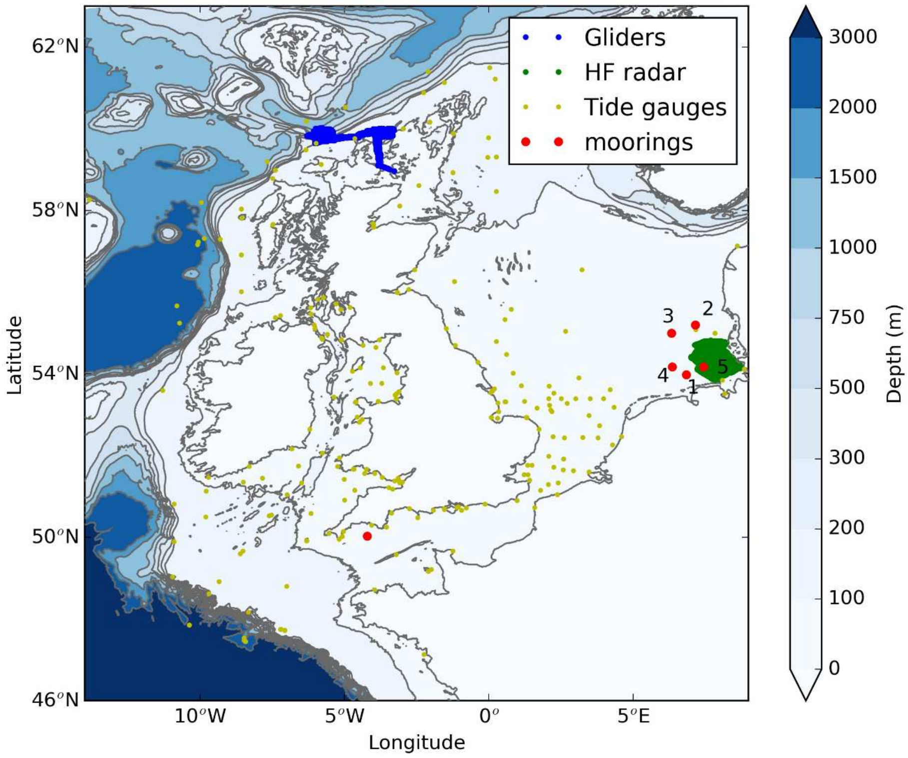

Figure 54: Maps of the independent observations used for validation. MASSMO4 Gliders are blue, COSYNA HFradar in the German Bight in green and the mooring in the German Bight in red, and the tide gauges in yellow..

The basin scale validation results for AMM7 and AMM15 are summarized in ~~the~~ Table 76 (with the system that has the best quality highlighted in bold), with a short description of the observations used. The ambition is to validate all the variables delivered to the users, even if there is a huge difference in the number and quality of observations available for the different parameters.

The RMS Difference and mean error (or bias) values are similar between the two systems and do not reflect the AMM15 system's superior performance as the validation at basin scale, averaged on the whole two years or one year period, penalises the high-resolution system. Whilst higher resolution models (subjectively) generate more realistic fields, it is often the case that statistics based on direct point match-up between interpolated model and observations do not improve due to the double penalty effect (e.g. Brassington, 2017). So, although global statistics do not show significant improvement from AMM7 to AMM15, it is demonstrated below that AMM15 consistently performs better than AMM7 when validated locally against high resolution observations. It is an active area of research both with the ocean and Numerical Weather Prediction communities to understand how to quantitatively demonstrate skill improvement from higher resolution systems, and something that needs a real focus from our community.

Table 7~~76~~: Synthesis of the validation results for AMM7 and AMM15.

Variable	Location	Supporting observations	RMS Difference		Mean Error (observation-model)	
			AMM7	AMM15	AMM7	AMM15
M2 tidal harmonic (amplitude)	Full domain	Tide gauge data	10.4 cm	**9.8 cm**	**-0.2 cm**	-4.6 cm
M2 tidal harmonic (phase)	Full domain	Tide gauge data	12.4°	**12.3°**	**-2 °**	4.2°
SST	Full domain	In situ observations	**0.45**°C	0.48°C	-0.01°C	-0.01°C
	Continental shelf	In situ observations	**0.51**°C	0.54°C	-0.02°C	-0.02°C
SST	Full domain	OSTIA satellite L4	0.34°C	0.34°C	**-0.06**	-0.08
T profiles	Full domain	In situ observations	0.47°C	**0.43**°C	-0.04°C	**0.02**°C
S profiles	Full domain	In situ observations	0.13~~3~~ PSU	**0.11**~~3~~ PSU	0.01 PSU	-0.01 PSU
SSH	Off-shelf	Altimeter from satellite	0.09 m	0.09 m	-0.01m	0.01m
	Continental shelf	Altimeter from satellite	0.13 m	**0.11** m	-0.06 m	**-0.02** m

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4.1 Tides

Most of the continental shelf seas dynamics is dominated by tidal variability, which impacts the velocity fields and plays a key role in the mixing and the generation of fronts. The improved resolution per se doesn't imply an improvement in capability to model the tidal signal even if differences in the topography and coastlines could affect the baroclinic component of the tide influenced by interaction of the flow with the bathymetry. This is particularly true in shallow areas when tidal currents are strong. We have assessed the tides for year 2016 and 2017 using the tidal gauges. In addition, we used HF radar velocity data available in a small part of the domain, in the German Bight (South-East North Sea), for a single month, March 2017.

4.1.1 Tidal harmonics

A harmonic analysis of the dominant tidal constituents was compared against tide gauge observations from BODC (British Oceanographic Data Centre, https://www.bodc.ac.uk/data/hosted_data_systems/sea_level/uk_tide_gauge_network/) and NOOS (North West Shelf Operational Oceanographic Service, http://noos.eurogoos.eu/). The number of tide gauges taken into consideration for AMM15 and AMM7 is the same, therefore the coastal –data~~buoys~~, not resolved by the AMM7 coastline, are not taken into consideration. AMM15 has a high horizontal resolution but since the model applies a minimum

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depth of 10 m (same as AMM7), the inaccuracy in depth can still affect its ability to properly estimate the tidal speed very close to the coast (Graham et al., 2018a). The statistics for the 7 dominant tidal constituents are detailed in Table 8~~Table 8Table 7~~. The differences in amplitude between AMM7 and AMM15 are small. AMM15 has consistently lower RMSD for the phase of the tide, although the phase bias is similar or higher in AMM15.

Table 8~~87~~: RMSD and bias of the tidal amplitude and phase of the prevalent tidal constituents. The value are means over 292 tide gauges for both AMM7 and AMM15. The value in bold indicates an improvement.

Tidal Constituent	**Amplitude (cm)**				**Phase (deg)**			
	RMS Difference		**Mean Error**		**RMS Difference**		**Mean Error**	
	AMM7	**AMM15**	**AMM7**	**AMM15**	**AMM7**	**AMM15**	**AMM7**	**AMM15**
M2	10.4	**9.8**	**-0.2**	-4.6	12.4	**12.3**	**-2.0**	4.2
S2	4.1	4.1	**-1.1**	-1.8	14.3	**13.4**	**-3.5**	5.5
K1	1.7	**1.6**	**-0.6**	-0.7	18.1	**17.4**	**4.1**	5.1
O1	2.1	**1.3**	1.5	**0.0**	19.6	**14.1**	**1.7**	2.5
N2	4.2	**3.7**	-0.6	**-0.3**	31.0	**26.7**	-4.4	**2.6**
Q1	1.7	**1.4**	-0.8	**0.1**	34.7	**34.0**	-11.3	**2.0**
M4	4.8	**4.5**	**-1.0**	-1.9	89.6	**66.8**	**-2.8**	15.3

While the performance of AMM7 and AMM15 is similar (Table 7) for basin means, anomalies vary across the domain, showing regional improvements (Graham et al. 2018a).Figure 6~~Figure 5~~ shows the spatial distribution of the M2 tidal errors in the two models. The values of RMS and mean error (~~model-~~observation-model) for amplitude and phase are very similar.

The M2 amplitude tends to be somewhat underestimated in the south-west part of the North Sea and along the east coast of the UK. Phase errors, in both models, are largest in the southern North Sea and off the north-eastern coast of Northern Ireland. The AMM15 M2 amplitude is more accurate in the western part of the basin, in particular around the Kintyre peninsula as already described in Graham et al.(2018a), and in the Bristol channel area. The AMM15 phase error is smaller than AMM7 in the German Bight (South-East North Sea) but not in amplitude.
There are no significant differences in the co-tidal chart (not shown) between AMM7 and AMM15, both are very similar to the charts shown in Graham et al. (2018a).

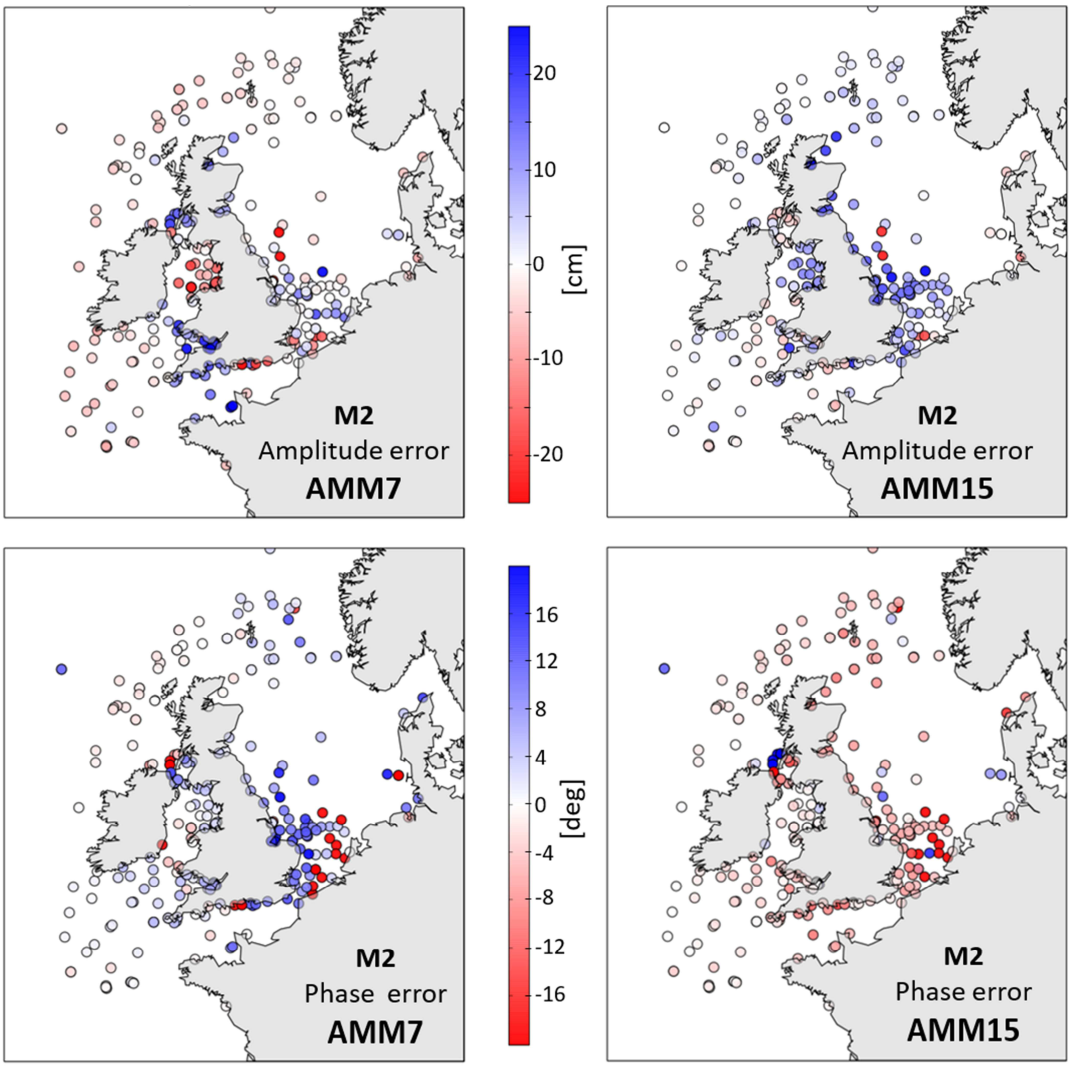

Figure 6~~5~~ : M2 Amplitude (top) and phase (bottom) error relative to observations (observations-model) for AMM7 (left) and AMM15 (right).

4.1.2 Tidal flow

~~The HF radar data used here are for one month, March 2017, of total surface velocity estimated from 3 WERA HF radar systems deployed in the German Bight (Gurgel et al., 2011) as part of the COSYNA (Coastal Observing System for Northern and Arctic Seas) observing network (Figure 4). Data are available through the EMODnet Physics data portal. At the operating frequencies used, the total surface velocities represent an integrated velocity over a depth between 1 and 2 m. The HF radar data are averaged every 20 minutes on a grid of resolution of ~3 km.~~One month, March 2017, of HF radar surface current velocity data were used to compare AMM7 and AMM15 in the German Bight where the bathymetry is shallow (Figure 4) and AMM15 is expected to performed better. The total surface velocity data from the COSYNA (Coastal Observing System for Northern and Arctic Seas) observing network (Gurgel et al., 2011), available through the EMODnet Physics data portal, are computed from radials of three HF radars installed on the islands of Sylt and Wangerooge, and in Büsum (as shown on Figure 6). Data are averaged every 20 minutes on a grid of resolution of ~3 km. At the operating frequencies used, the total surface velocities represent an integrated velocity over a depth between 1 and 2 m. Relative error provided with the dataset was used to keep only data with error smaller than 15%. Model output were interpolated at the time and locations when and where observations were available to avoid applying gap-filling technics. Temporal coverage over the domain is larger than 75% everywhere except along the base line between Büsum and Wangerooge where the temporal coverage is ~29%.

Because the high frequency variability of the flow in the German bight is dominated by tidal flow, a low pass filter was applied to the data with gaps,~~used~~ to separate the tidal and the residual component of the velocity. The tidal flow assessment presented here uses the high-pass filtered data (Figure 7~~Figure 6~~); the residual currents that come from the low-pass filtered data are discussed in ~~Section 4.5~~the next Section, 4.2. Vector correlation (or complex correlation of $u+iv$, where u and v are the zonal and meridional velocity respectively, and i is the square root of -1) were estimated and are displayed as correlation amplitude, and phase, or veering. The phase represents the rotation between the two vectors that gives the highest correlation.

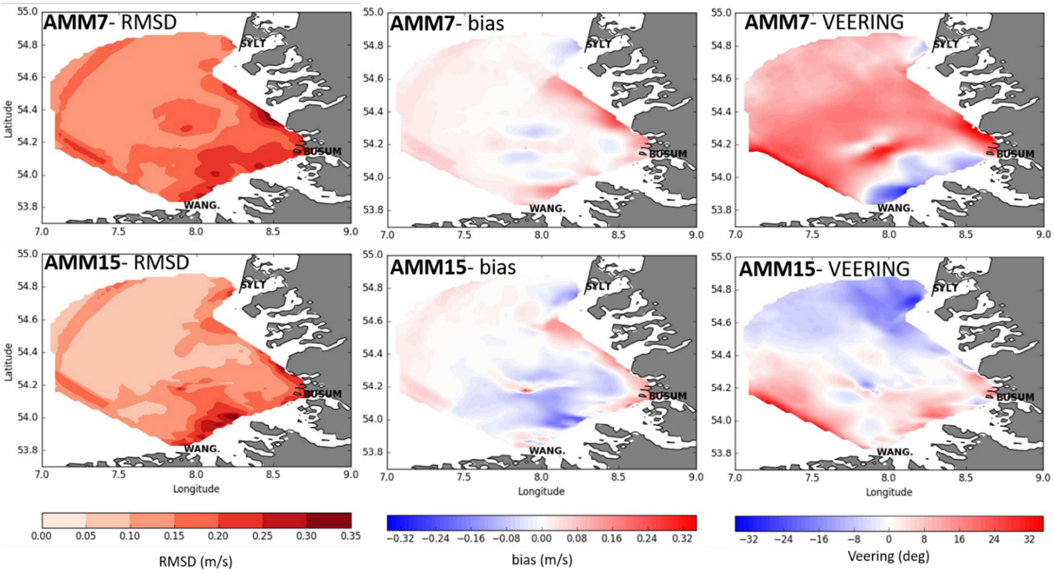

Figure 7~~6~~: plots of statistics between HF radar surface current observations and AMM7 (top) and AMM15 (bottom) for the high-passed filtered data (tidal signal). Bias (observation-model) and RMSD (in m/s) are estimated on the velocity vector magnitudes. Right panel: phase or veering. Positive (negative) veering represent a clockwise (counter-clockwise) angle of AMM7 (top) or AMM15(bottom) vectors with respect to the HF radar vectors. SYLT, WANG and BUSUM show the locations of the three HF radars on the islands of Sylt and Wangerooge, and in Büsum respectively.

The various metrics show that AMM15 resolved the tidal current in the south German Bight better than AMM7, as shown in Figure 7~~Figure 6~~. Although AMM15 bias is slightly higher than AMM7 in some areas, RMSD of AMM15 is smaller than the RMSD of AMM7 everywhere in the HF radar domain.

Both models show high correlation with the observations (not shown) and AMM15 has a lower phase, veering, with the observations. Because tidal velocities are rotating periodic signals, the spatial angular veering estimated using the complex correlation can also be interpreted as a temporal phase of the tidal signal. Positive veering angle means that the model tidal velocities lead the HF radar tidal velocities. Figure 7~~Figure 6~~ shows that the tidal phase is improved in AMM15 compared to AMM7 in most of the domain, consistent with the results of the comparison with the tide gauges, 4.1.1.

4.2 Surface currents in the German Bight

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A good forecast of the intensity and direction of the currents is needed for operations at sea, but the validation of this variable is particularly difficult due to the scarcity of observations. There are very few measurements of velocity in the model domain. Among the few data available we have decided to use the surface currents measured by the HF radar.

The HF radar data used here are one month of total surface velocity currents estimated from three HF radar installed in the German Bight, described in the Section above, 4.1.2 Tidal Flow.

Because the high frequency variability of the flow in the German Bight is tidally dominated, a low pass filter was used to separate the tidal and the residual component of the velocity. Statistics were computed on the high-pass and low-pass filtered velocity components to assess the tidal and residual flow respectively. The assessment of the tidal flow is described in section *4.1.2. Tidal Flow* while this section focuses on the sub-tidal circulation.

The strong tidal signal in the shallow German Bight results in Kelvin waves propagating eastward on the southern boundary along Germany and northward at the eastern boundary along Denmark. However, this cyclonic circulation may not dominate as other processes are also influencing the circulation such as topographic effects from the shallow basin, wind and stratification resulting from freshwater input mostly from the Elbe and Weser river discharge. Wind tends to also produce a residual cyclonic circulation (Schrum 1997, Dick et al 2001, Port et al 2011). During the month of March 2017, a weak cyclonic circulation was observed in the mean HF radar surface currents along the German and Danish coasts (Figure 6). It is also observed in the AMM15 simulations and as a weaker flow in AMM7. The strong flow out of the Elbe estuary is evident in AMM15 currents pattern, even if shifted to the west. AMM7 shows an intensification of its currents in this area, but with a speed much smaller than the observations and AMM15 (Figure 6). Generally, the spatial variability observed in HF radar is better captured by AMM15 than AMM7 (~~Figure 16~~). Similar statistics as those estimated for the tidal flow (Figure 7~~Figure 6~~) also show improvement in both amplitude and direction of the residual flow (not shown).

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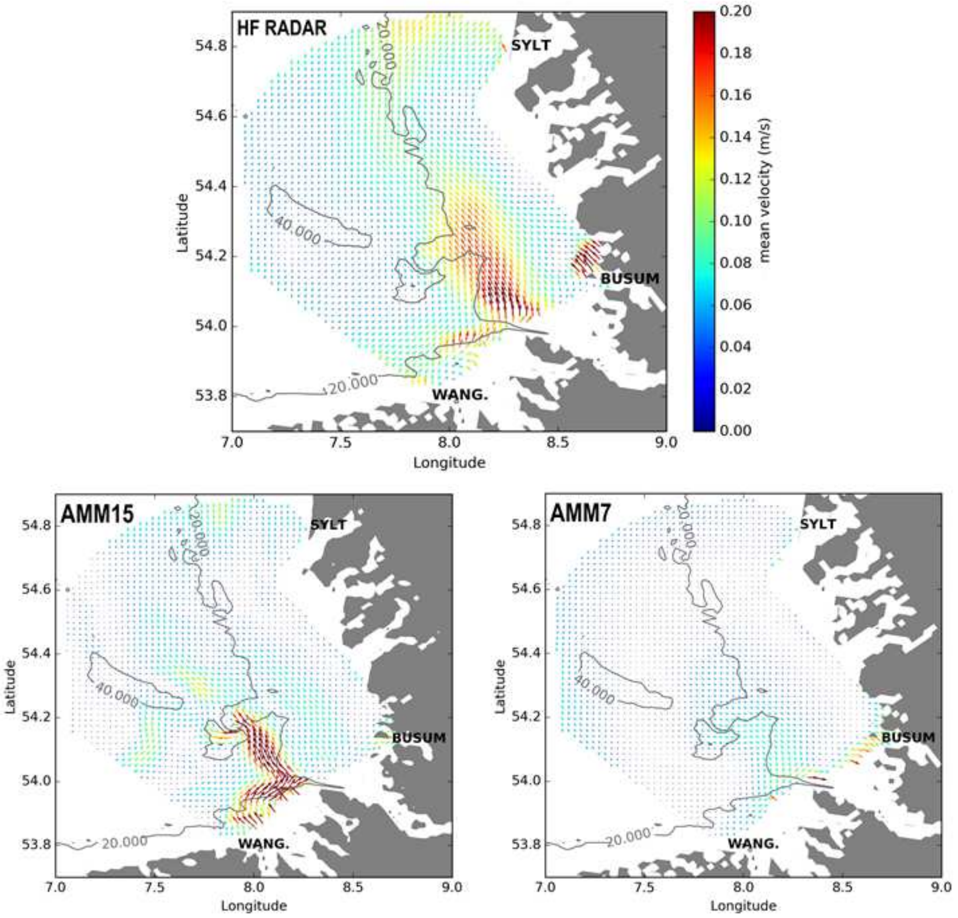

Figure 8~~16~~: March 2017 average surface flow for HF radar (top), AMM7 (bottom left) and AMM15 (bottom right). Model data are re-gridded on the HF radar grid using cubic interpolation. The hourly model output is linearly interpolated every minute to match the HF radar observations. Model output are only plotted where HF radar data are available. Grey lines represent the 20 and 40 m bathymetric depth. SYLT, WANG and BUSUM show the locations of the three HF radars on the islands of Sylt and Wangerooge, and in Büsum respectively.

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4.~~2~~ 3 Sea Surface Height

AMM15 and AMM7 SSH is assessed against the satellite Sea Level Anomaly data used for the data assimilation both on and off the shelf (Table 7~~Table 6~~), matching the model to the observation before the SSH data assimilation. The matchups are created by interpolating the model field to the observation location, at the model time step nearest to the time of the observations. It is worth noting that the assimilation of SLA is done only where the bathymetry is deeper than 700m, therefore no observations are assimilated on shelf and in a large part of the off-shelf region. The differences between AMM15 and AMM7 are negligible both on the continental shelf and off shelf. As expected in a tidally dominated area, on the continental shelf the RMSD is slightly higher than off shelf: 0.13 m on-shelf and 0.09 off-shelf. Both models are overestimating the SSH on shelf, but AMM15 has a smaller bias (-0.02m AMM15 and -0.06m AMM7). Instead, off-shelf AMM15 and AMM7 have the same absolute value of bias (0.01 m) but opposite sign, positive for AMM15 and negative for AMM7.

4.~~3~~ 4 Sea Surface Temperature

Sea surface temperature is one of the key parameters of heat exchange at the air-sea boundary. Thanks to satellite and in-situ observations, SST is the variable with the best measurement coverage in our model domain. SST data is assimilated in the AMM15 and AMM7 models (Figure 4) during the Incremental Analysis Update (IAU) step of each model run. As a result, an assessment of the model skill at predicting SST compared to observations would be expected to produce a positive result. We have compared the model against all the assimilated observations, the OSTIA products and a number of time series at selected moorings. It's worth to notice that while the comparison with the assimilated observations is done using the model output at the nearest time step, the comparison against OSTIA is done using the daily means. The hourly instantaneous fields are used instead for the comparison at the mooring locations. This validation allows us to have a general overview of the model SST performance with a detailed analysis of the high-resolution model in few selected locations.

4.~~3~~4.1 Comparison with in situ and satellite

Model SST has been assessed here against in-situ SST measurements matching the model to the observation before the data assimilation, at the model time step closer to the observations time. The in-situ measurements are from ~~buoys and ships of opportunity~~different instruments, as detailed in Table 3. The number of the in-situ SST observations is pretty good during the two years: ~1000 obs/day on the full model domain of which ~500 on-shelf. The differences between the two systems, in the full model domain, are very small (Table 7~~Table 6~~). The RMSD is ~0.5°C for both AMM7 and AMM15. Both models have a small warm bias, -0.01°C, over the full period. The warm bias is mainly due to the winter months when the model is slightly warmer than the observations. The same statistics on-shelf shows very similar results.

In addition to the in-situ observation assessment, the model hourly SSTs have been compared to the Met Office's Operational Sea surface Temperature and sea Ice Analysis (OSTIA) system (Donlon, et al., 2012). OSTIA provides analyses of the foundation SST (i.e. the SST free of diurnal variability) and assimilates in-situ and satellite observations. The OSTIA data, available through the CMEMS~~opernicus Marine~~ catalogue, is produced on a 1/20°grid (~6km resolution), however, this is not the feature resolution of the product, which depends on other aspects of the system such as the correlation length scales used in producing the analysis. OSTIA has a maximum feature resolution of ~20-30 km and so both AMM7 and AMM15 are expected to represent smaller features than OSTIA. The important point to consider in this assessment is that OSTIA foundation SST is being compared to the model surface box daily mean SST that should be biased warm compare to foundation.

The reference grid used for the inter-comparison of these three datasets is AMM7, therefore OSTIA and AMM15 have been interpolated at 7km.

The bias is defined as observation-model. Both models are biased warm compared to OSTIA (Figure 9~~Figure 7~~), in agreement with the in-situ-model matchups statistics. AMM15 has a slightly higher bias than AMM7 but the same RMSD. The high variability of the signal in AMM15 could be penalized by the interpolation onto a grid at lower resolution. Overall, we see little difference in performance between the two systems. The mean RMSD for the period 2016-2017 is for both the systems of 0.3°C, smaller than the RMSD computed by the in-situ-model matchup statistics (0.5°C). The comparison between OSTIA-model and insitu-model differs also because OSTIA comparison uses a full field to calculate the statistics rather than the single-point observation used in the insitu-model matchups.

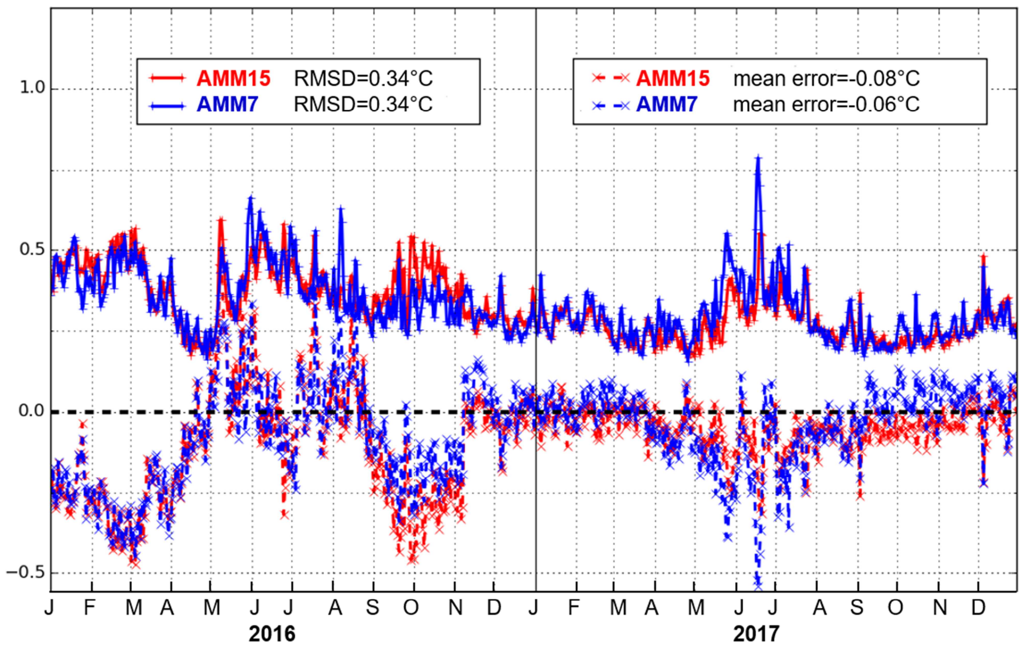

Figure 9~~7~~: OSTIA minus Model SST RMSD and bias daily comparison for AMM7 (blue) and AMM15 (red) for the whole domain (negative mean error indicates a warm model bias).

4.~~3~~4.2 Variability in SST

A small number of buoys have been used to investigate the SST variability in the models (Figure 5~~Figure 4~~). Three sites were investigated in this study, E1 (50.026°N, 4.225°W) in the English Channel and the FINO sites in the German Bight (FINO1 at 54° 00.89 N, E 6°35.26 E and FINO3 at 55°11.7 N 7°9.5 E), buoys marked as 1 and 2 in Figure 5~~Figure 4~~. In the future it would be helpful to get a broader range of sites included. A Butterworth filter (Butterworth, 1930) has been applied to the hourly model and observed SST data, using a cut-off for the filter at 5 days which removes the large scale synoptic and seasonal signals, leaving the internal dynamics and the wind driven signals, as well as the tidal frequencies.~~to remove low frequency (periods greater than 5 days) signals in the SST timeseries, to allow a comparison of the high frequency changes only~~. The observation data were interpolated hourly to be equivalent to the model data, and the precision of the model data reduced to the same precision as the observations, to allow direct comparison and to prevent any aliasing. The timeseries were divided into seasons, both due to the high seasonal variability of SST and to avoid observation data gaps that would skew the analysis. We defined the four seasons as: December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September, October, November (SON). The data used for this study covers the period December 2016-November 2017.

The model data was taken from the analysis day. It would be interesting to also assess the forecast, this will be the subject of future studies. Figure 10~~Figure 8~~ shows the SST and filtered SST timeseries at the FINO3 mooring for two different seasons, winter (DJF) and summer (JJA). The filtered SST signal has a higher variability in summer when the diurnal warming is stronger and therefore the SST gradients are bigger. AMM7 and AMM15 have very similar values of SST, probably due to the data assimilation of SST that brings both models close to the observations.

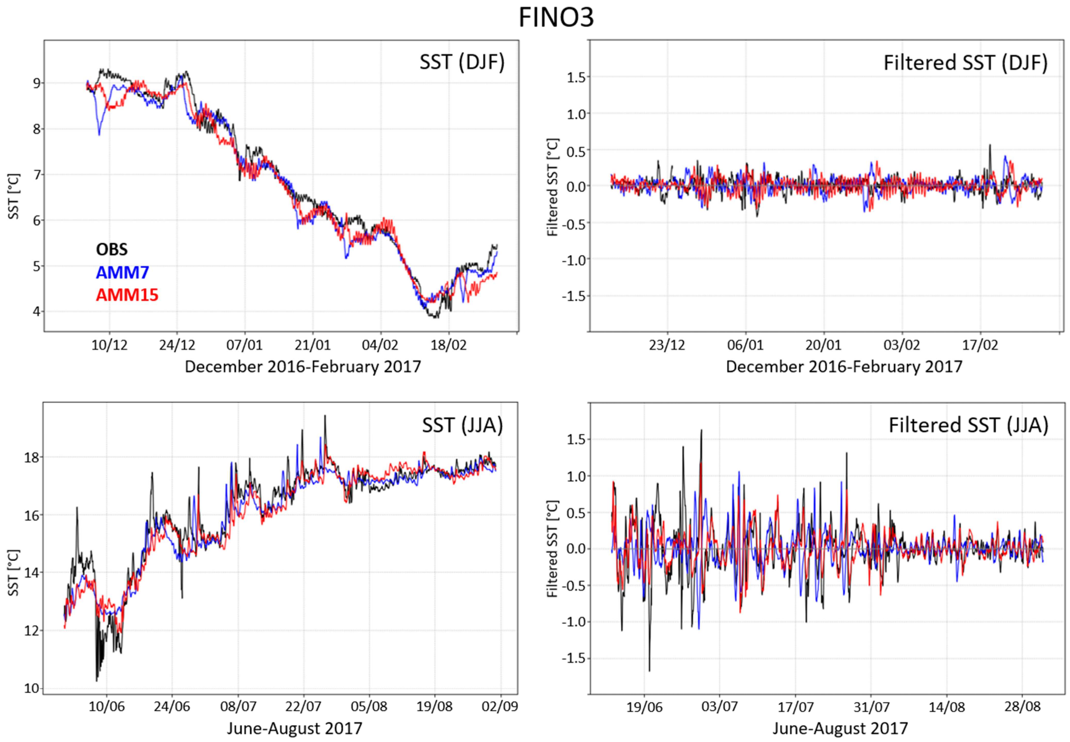

Figure 10~~8~~: Timeseries of sea surface temperature (left) and filtered SST (right) for the FINO 3 buoy for December 2016-February 2017 (top) and June-August 2017 (bottom). Observations are shown in black, AMM7 in blue and AMM15 in red.

Spectral powers were estimated and smoothed using a Loess filter to remove noise in the spectra. Figure 11~~Figure 9~~ shows the power spectra for each season at the FINO 3 buoy, the non-filtered spectra are also plotted as faint lines. The power spectra of SST at the other mooring locations, E1 and FINO1, are not shown but are similar to FINO3. Although this is not exclusively true, the general trend is for the models to drop off in power more quickly with frequencies, and have a steeper spectral slope, than the observations. AMM15 SST is more variable at frequency higher than daily, although at periods of 4 hours and lower the models tend to behave quite similarly. This is consistent with what one would expect from the mesoscale resolving skills of AMM15. This high frequency increase of variability in AMM15 compared to AMM7 can also be seen by quantitative inspection of the model fields (Figure 10~~Figure 8~~), with small length scale features being more prevalent in AMM15. At higher frequencies (shorter periods) SST spectra for both models collapse to the same power spectrum value with generally less variability than the observations at high frequencies.

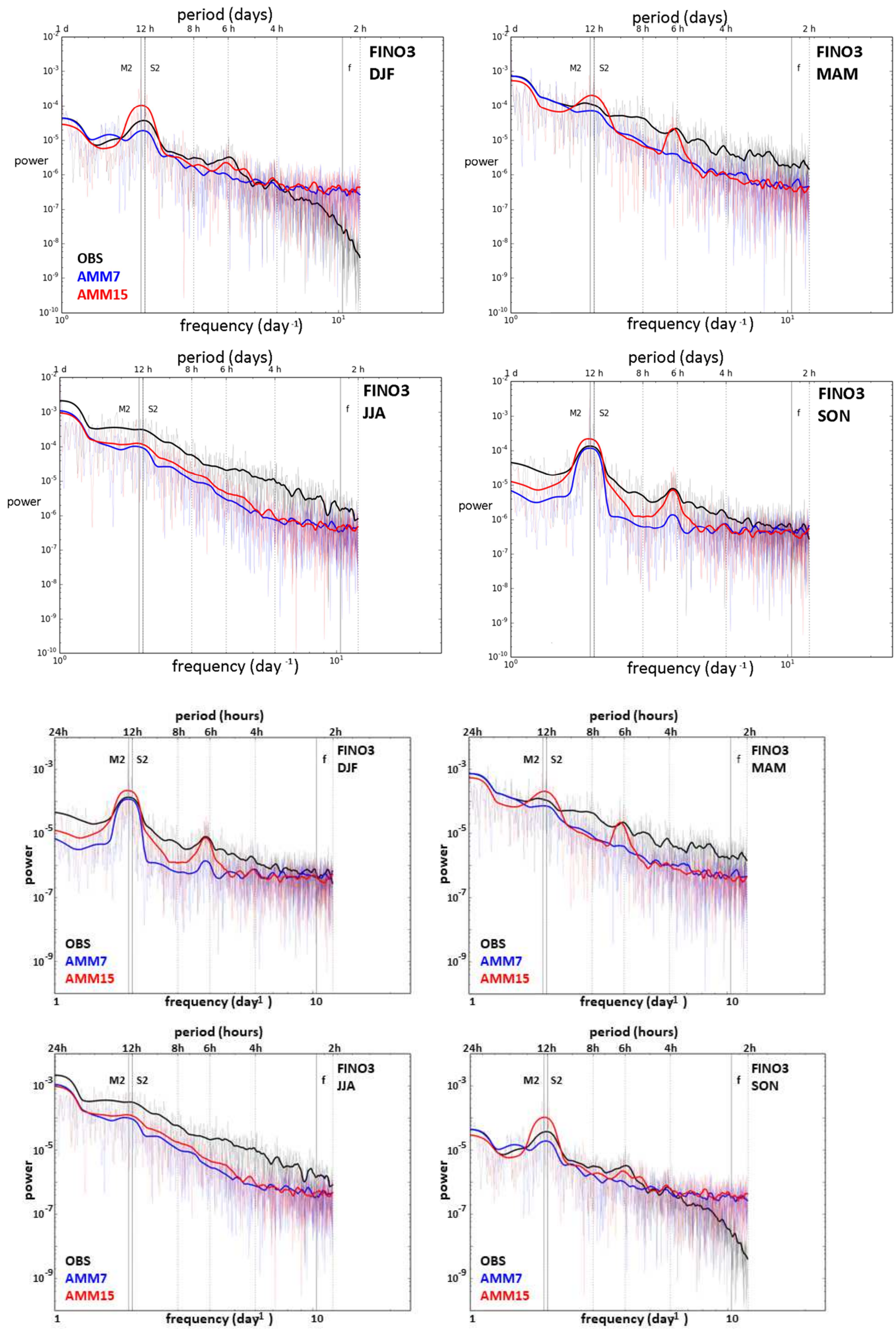
period (days)
FINO3
DJF
FINO3
MAM
FINO3
JJA
FINO3
SON
M2
S2
f
power
frequency (day⁻¹)
OBS
AMM7
AMM15
period (hours)
frequency (day⁻¹)

Figure 11~~9~~: Power spectrum of SST for the FINO3 buoy (black line) compared with the AMM7 (blue) and AMM15 (red) simulations for December 2016 to February 2017 (top left), March to May 2017 (top right), June to August 2017 (bottom left) and September to November 2017 (bottom right).

This suggests that on average some of the very high frequency / small scale features are still not being represented in the models, although it should be noted that the model represents a mean over a grid which will by definition introduce some smoothing, whereas the observations are (at least to a greater extent) sampling at a point. This analysis demonstrates quantitatively that the AMM15 better represents the high frequency / small scale features, which can visually be observed from model fields time series, but are poorly assessed through global statistics, as shown in Table 7~~Table 6~~. This result is likely to be even more pronounced in forecast fields, although that is not demonstrated here.

4.~~4~~ 5 Water column

4.~~4~~5.1 Temperature and salinity profiles

AMM15 shows improved vertical structure of the water column, with a lower bias and RMSD compared to AMM7 in salinity and temperature. Figure 12~~Figure 10~~ shows the mean error (obs-model) and the RMSD averaged over the whole domain, with observation-model differences calculated before the assimilation of the vertical profiles. The temperature bias of both models is very small at the surface but increases below 100m. Between 500 and 1000m AMM15 has a mean error close to zero, while AMM7 has a cold bias. AMM15 also has a lower RMSD than AMM7 at all depths below the surface. The distribution of the sub-surface observations, shown in Figure 3, is uneven, with very few observations on shelf, therefore it is not possible to distinguish between the water column improvements off-shelf and on-shelf using this technique, and these improvements are demonstrated predominantly for the off-shelf region. This is a very good result considering that the skills in modelling salinity and temperature depth structure have recently been significantly improved in AMM7 with the improvements in data assimilation, with the addition to SST of SLA and sub-surface profiles (King et al. 2018). This means that, in less than 2 years, the NWS system has consistently improved its skill in resolving the vertical profiles of temperature and salinity and therefore the density of the water column.

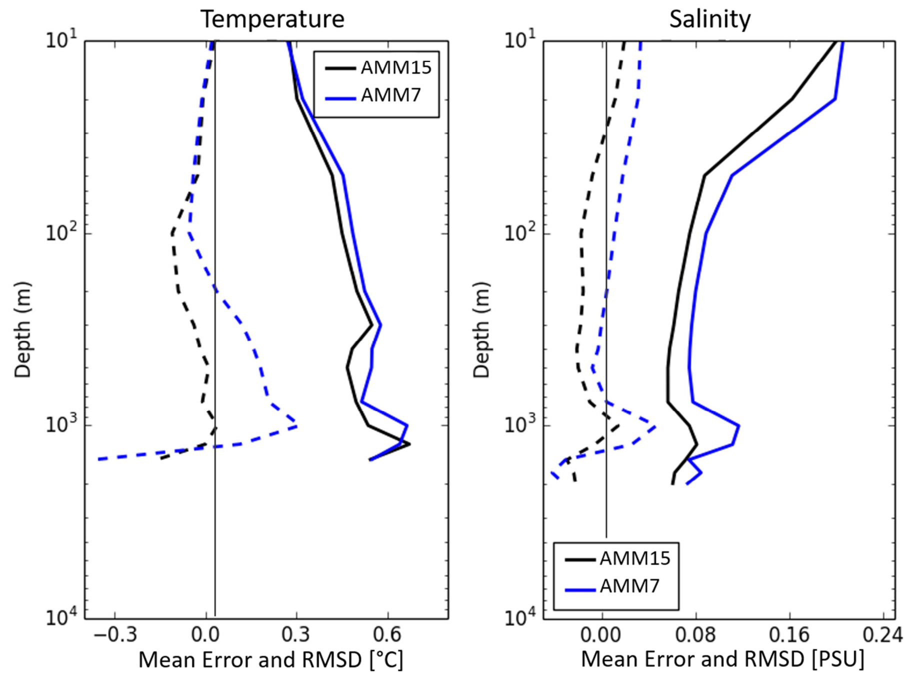

Figure 12~~10~~: Observation minus model temperature (left) and salinity (right) profile assessment for AMM15 (black) and AMM7 (blue) for the whole domain. The RMS difference is shown by the solid lines and mean error (observation-model) is shown by the dashed lines.

4.~~4~~5.2 Moorings in the German Bight

Table 9~~Table 8~~ and Table 10~~Table 9~~ show the temperature and salinity statistics for the model and observations comparison during year 2017 at the five moorings in the German Bight (Figure 5~~Figure 4~~). Observations for both temperature and salinity are available at surface (5m) and bottom. The models assimilate only SST observations, not salinity and no bottom observations. The hourly instantaneous model data are compared to the buoy observations with a few discontinuities due to missing measurements during a short period of the year. AMM15 has a better RMSD and a lower error mean at all buoy locations. The high frequency variability is better reproduced by AMM15 than AMM7, as shown in Figure 13~~Figure 11~~ for the surface salinity field in the NsbII (mooring number 3 in the map of Figure 5~~Figure 4~~).

Temperature RMSD and bias are very small at surface, due to the strong constraint of the data assimilation of SST (as described in 4.3) while at the bottom AMM15 is more accurate in prescribing the temperature at all mooring locations (Table 9~~Table 8~~).

AMM7 and AMM15 both have high salinity errors in the German Bight, as highlighted by the comparison with the buoys that are located closer to the coast (Fino1, Fino3 and UFSDeBucht). This is most probably due to representation of river discharge. AMM15 performs better than AMM7, probably because it is less diffusive within river plumes and has a lower lateral diffusion. Improved bathymetry and coastal resolution are also likely to play a role in coastal areas with depth less than 20m. AMM15 has halved the salinity error compared to AMM7 when compared with the outer buoys (NsbII and TWEms). It is encouraging to see that AMM15 is better than AMM7 at the bottom at all mooring locations. The decision to use the climatological river discharge dataset instead of E-Hype for AMM7, and subsequently AMM15, has improved salinity remarkably in the German Bight, reducing the model fresh bias. This modification was implemented in April 2017, meaning that we have significantly improved the salinity in the last two major updates of the NWS forecasting system. Nevertheless, using a climatological river runoff dataset is a limitation for a high-resolution forecasting system, affecting variability in coastal water properties. Finding a suitable alternative will be a priority for future releases of this system.

Temperature RMSD and bias are very small at the surface, due to the strong constraints of the data assimilation of SST (as described in 4.3) while at the bottom AMM15 is more accurate in prescribing the temperature at all mooring locations (Table 9~~Table 9Table 8~~).

Table 9~~9~~8: Yearly mean (2017) RMSD and bias statistics at the 5 moorings in the German Bight (observation-model). Surface and bottom temperature for AMM7 and AMM15.

Buoy [bottom depth]	Temperature (C°)							
	Surface				Bottom			
	RMS Difference		Mean Errors		RMS Difference		Mean Error	
	AMM7	AMM15	AMM7	AMM15	AMM7	AMM15	AMM7	AMM15
1 Fino1 [25m]	0.32	**0.21**	**0.03**	-0.05	0.31	**0.21**	0.07	**-0.03**
2 Fino3 [18m]	0.38	**0.37**	**-0.02**	-0.04	0.96	**0.59**	-0.38	**-0.24**
3 NsbII [35m]	0.30	**0.25**	0.12	0.12	0.59	**0.49**	**-0.13**	-0.14
4 TWEms [30m]	0.28	**0.26**	0.13	**-0.02**	0.28	**0.16**	0.11	**0.00**
5 UFSDeBucht [20m]	0.50	0.50	0.10	**0.01**	0.95	**0.75**	**-0.31**	-0.33
Mean value	0.36	**0.32**	0.07	**0**	0.62	**0.44**	**-0.13**	-0.15

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Table 10~~10~~9: Yearly mean (2017) RMSD and bias statistics at the 5 moorings in the German Bight (observation-model). Surface and bottom salinity for AMM7 and AMM15.

Buoy [bottom depth]	Salinity (PSU)							
	Surface				Bottom			
	RMS Difference		Mean error		RMS Difference		Mean Error	
	AMM7	AMM15	AMM7	AMM15	AMM7	AMM15	AMM7	AMM15
1 Fino1 [25m]	1.17	**1.02**	0.97	0.97	1.10	**1.02**	0.95	**0.95**
2 Fino3 [18m]	1.06	**0.73**	**0.35**	0.48	0.90	**0.62**	0.53	**0.38**
3 NsbII [35m]	0.33	**0.22**	0.20	**0.03**	0.37	**0.17**	0.26	**0.03**
4 TWEms [30m]	1.05	**0.51**	0.85	**0.29**	1.08	**0.45**	0.89	**0.26**
5 UFSDeBucht [20m]	**0.99**	1.07	**0.55**	0.87	1.08	**1.02**	**0.86**	0.90
Mean value	0.92	**0.71**	0.58	**0.53**	0.91	**0.66**	0.70	**0.51**

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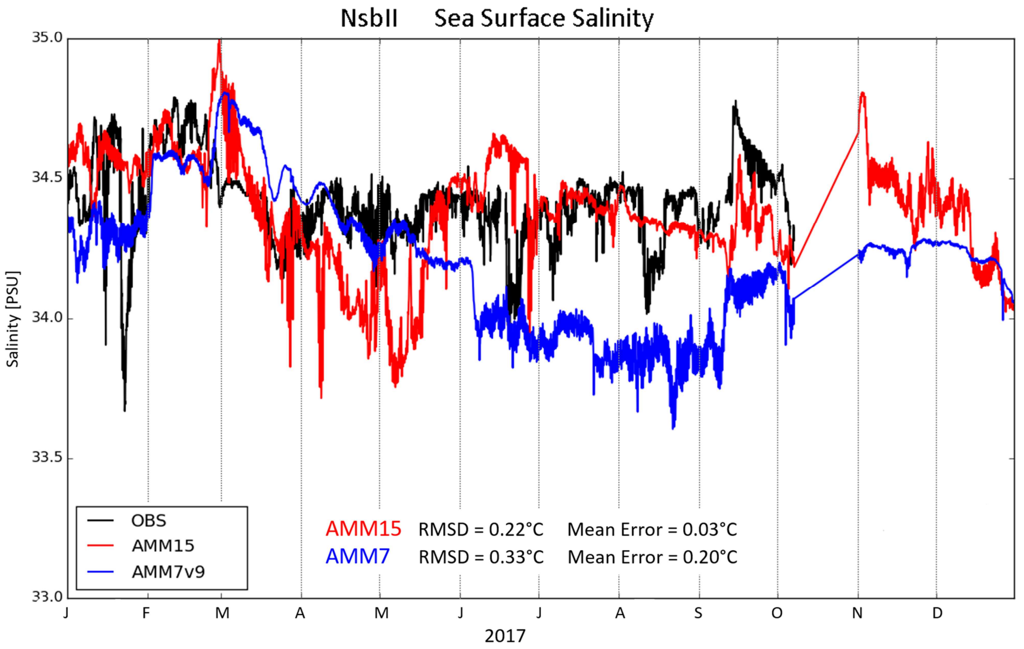
NsbII Sea Surface Salinity
Salinity [PSU]
35.0
34.5
34.0
33.5
33.0
J F M A M J J A S O N D
2017
OBS
AMM15
AMM7v9
AMM15 RMSD = 0.22°C Mean Error = 0.03°C
AMM7 RMSD = 0.33°C Mean Error = 0.20°C

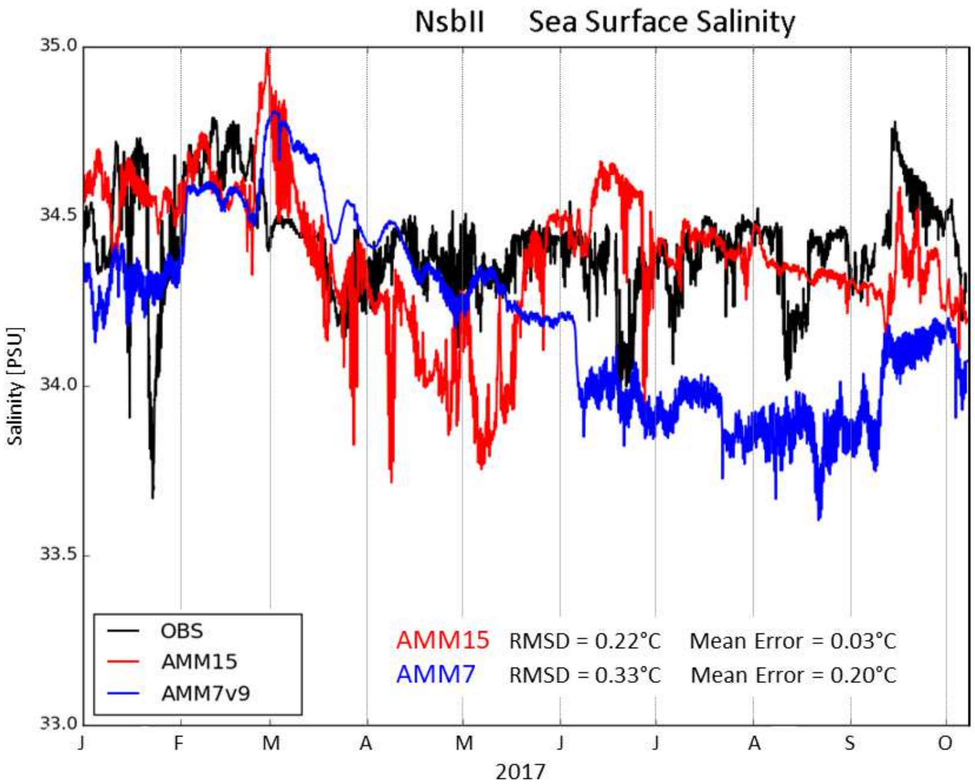
NsbII Sea Surface Salinity
Salinity [PSU]
35.0
34.5
34.0
33.5
33.0
J F M A M J J A S O
2017
OBS
AMM15
AMM7v9
AMM15 RMSD = 0.22°C Mean Error = 0.03°C
AMM7 RMSD = 0.33°C Mean Error = 0.20°C

Figure 13~~11~~: Sea surface salinity at the NsbII mooring for January-September ~~year~~ 2017. The blackline represents the observations, while the red and the blue respectively AMM15 and AMM7. Observations are missing for the period October-December.~~AMM15 red line, AMM7 blue line, observations black line.~~

4.~~4~~5.3 Glider transects

AMM15 and AMM7 vertical structure and high frequency variability is assessed against the glider profiles from MASSMO (Marine Autonomous Systems in Support of Marine Observations), Mission4 (Figure 5~~Figure 4~~ and Figure 14~~Figure 12~~). MASSMO is a pioneering multi-partner series of trials and demonstrator missions that aim to explore the UK seas using a fleet of innovative marine robots. With newly developed unmanned surface vehicles (USVs) and submarine gliders, the multi-phase project has successfully completed the largest single deployment of marine autonomous systems ever seen in the UK. In the summer of 2017 a fleet of 11 autonomous marine robots was deployed to explore the seas northwest of the Orkney Islands in search of marine mammals and sources of man-made noise pollution. The mission was part of an annual series of marine robot trials co-ordinated by the National Oceanography Centre in partnership with 16 organisations representing UK government, research and industry (http://projects.noc.ac.uk/massmo).The fleet comprised eight submarine gliders and three unmanned surface vehicles, travelling up to 200km offshore to the Faroe-Shetland Channel where water depths exceeded 1000m. The MASSMO4 campaign covered the period 22nd May to 6th June 2017 with 3 gliders deployed north of Scotland, close to the coast, and then travelled across the shelf break (Figure 5~~Figure 4~~).

The MASSMO4 dataset is therefore a very high-resolution source of information in a key area of the model domain. We have compared the models and observations along the glider track, using the model high frequency data (hourly instantaneous fields). Figure 14~~Figure 12~~ shows the trajectory of one of these gliders (553), which was measuring temperature and salinity from surface to bottom. The background field in this figure shows surface salinity from AMM15 at 12:00 UTC of 23rd May, when the glider was in the position marked by the red dot.

AMM15 is in very good agreement with the observations and shows improvement, compared to AMM7(Figure 15~~Figure 13~~ and Figure 16~~Figure 14~~), particularly for salinity along the glider trajectories. The only exception being the low salinity pattern in the whole water column measured by the glider around the 23rd of March, when AMM15 is too salty and AMM7 too fresh. It could be due to a misplaced of a front, as suggested by the AMM15 salinity map (Figure 14~~Figure 12~~). The AMM7 salinity field (not shown) has lower variability and this could justify the smaller misfit compare to the glider in that precise location.

The salinity field in AMM15 has finer scale structures and usually the low salinity is better constrained along the coast. The density of the water column during the period of the gliders campaign is therefore much more accurate in AMM15 (Figure 17~~Figure 15~~). While these results may not be representative of the whole model domain or of the seasonal variability in stratification of the water column, they are very encouraging.

In all depth profiles for AMM7, there is a white patch close to the bottom on the 23/05. This is due to the model bathymetry being shallower than the reality in that specific location. This is a confirmation than AMM15 has a more realistic representation of the bottom topography, as described in Section 2.1 Core Model Description.

The increased resolution of fine-scale structures in AMM15 results in increased transport across the shelf-break, particularly in the region observed here (Graham et al 2018b). These results, showing AMM15 has improved vertical structure and variability of the water column, support the conclusions of Graham et al. (2018b). Shelf-break processes transporting water masses between the deep ocean and across the shelf, will have a strong impact on conditions observed in this region.

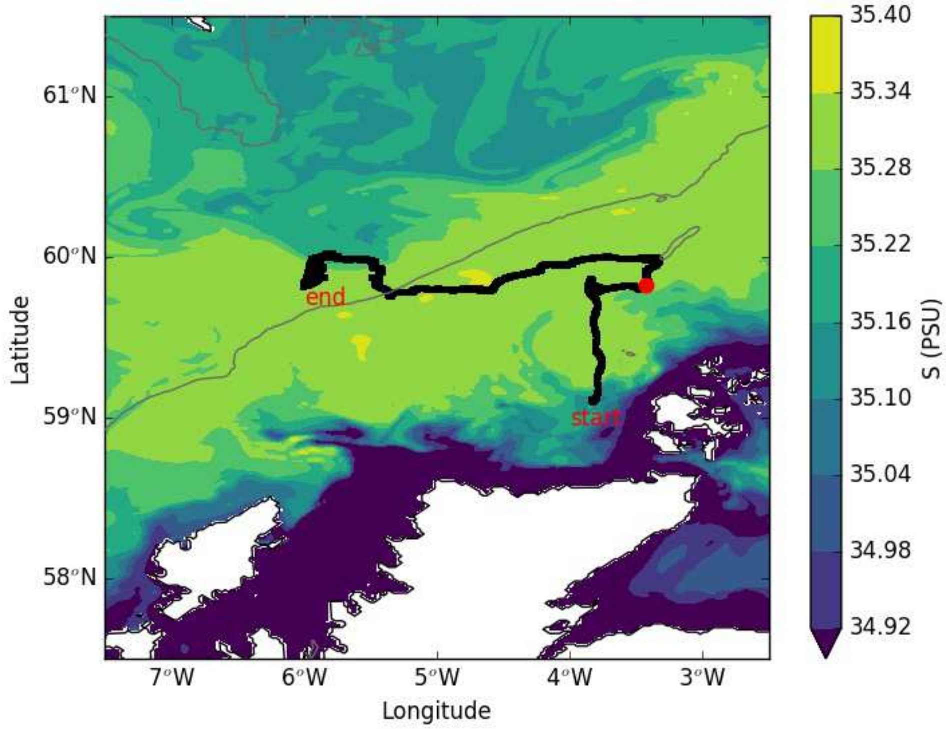

Figure 14~~12~~: Glider 553 trajectory. The glider started the measurement close to the Scotland coast, and then moved towards the shelf break. The black line is the glider trajectory. The grey line represents the 200m isobath. The red dot is the glider position on the 23rd ~~t~~ May 2017. The field on the background in the salinity on the 23rd of May.

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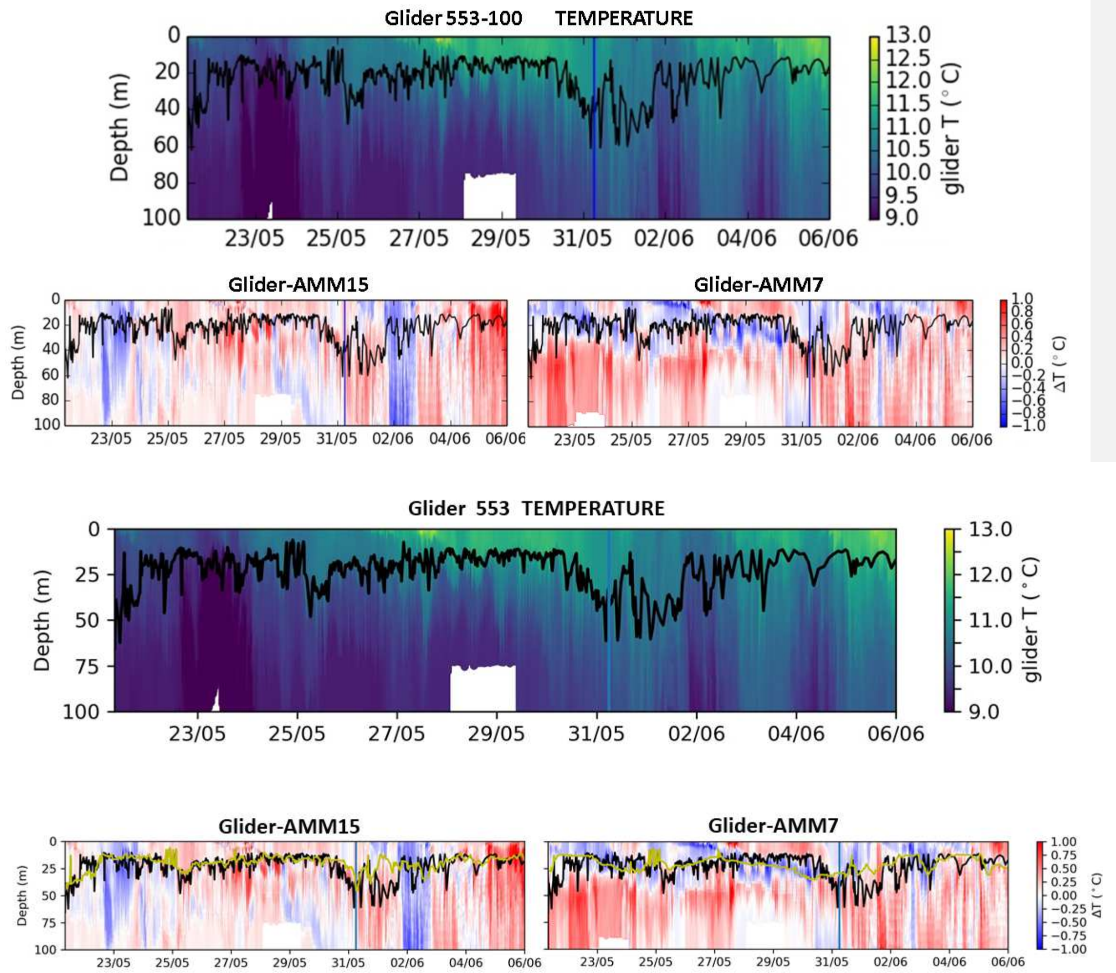


Figure 15~~13~~: Top 100m of temperature profile along glider 553-100 trajectory. Top panel: temperature measured by the Glider. Bottom left: difference glider-AMM15. Bottom right: difference glider-AMM7.The vertical blue line represents when the glider goes over the shelf break, crossing the 200m isobath. Before that time the glider is on the shelf. The black line is the MLD computed from the glider measurements, the yellow line is the model MLD.

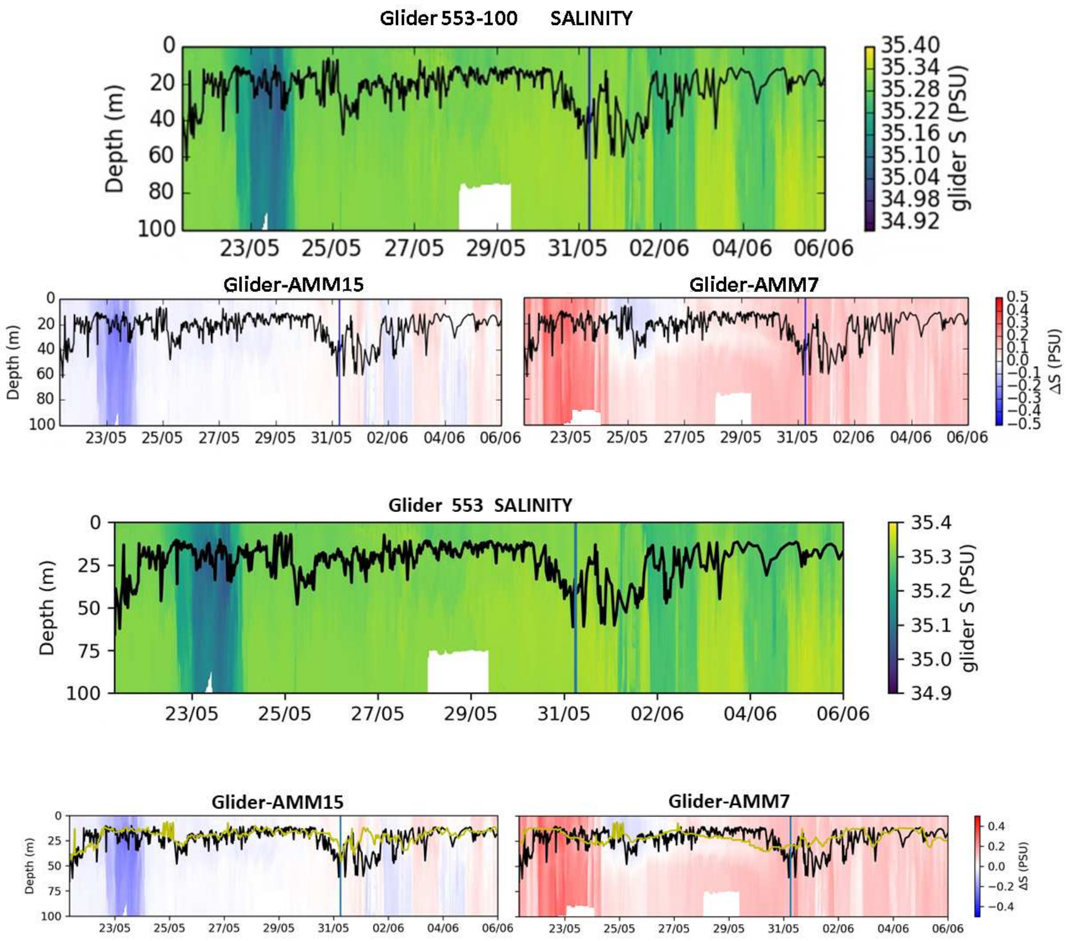
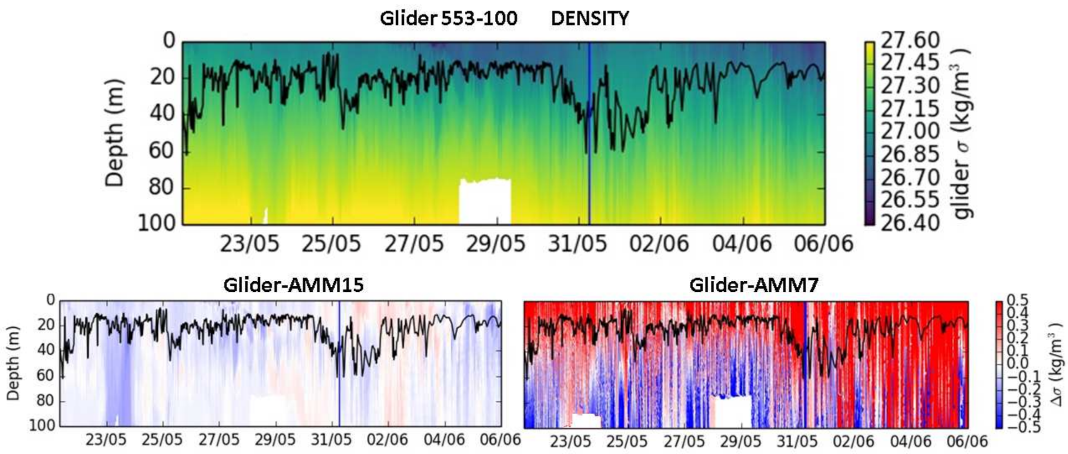


Figure 16~~14~~: Top 100m of salinity profile along glider 553-100 trajectory. Top panel: salinity measured by the Glider. Bottom left: difference glider-AMM15. Bottom right: difference glider-AMM7.The vertical blue line represents when the glider goes over the shelf break, crossing the 200m isobath. Before that time the glider is on the shelf. The black line is the MLD computed from the glider measurements, the yellow line is the model MLD.



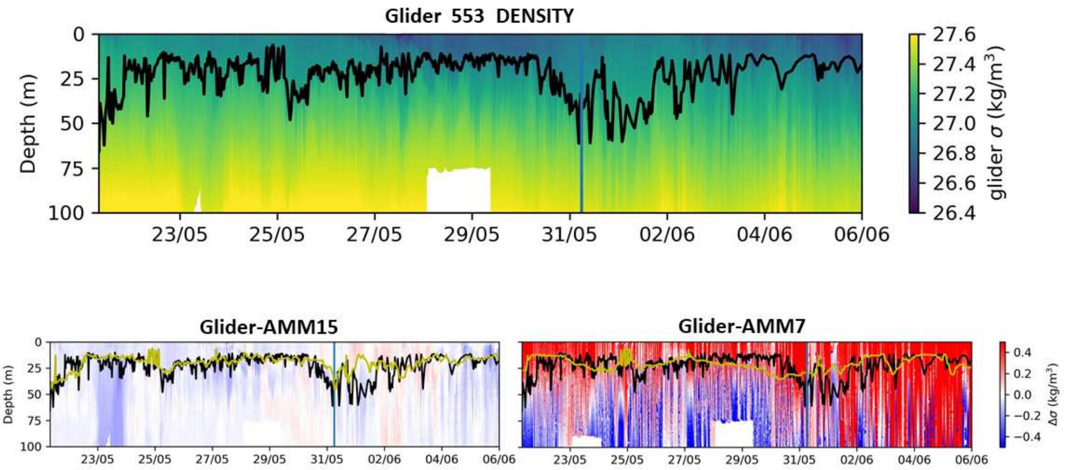


Figure 17~~15~~: Top 100m density profile along glider 553-100 trajectory. Top panel: salinity measured by the Glider. Bottom left: difference glider-AMM15. Bottom right: difference glider-AMM7.The vertical blue line represents when the glider goes over the shelf break, crossing the 200m isobath. Before that time the glider is on the shelf. The black line is the MLD computed from the glider measurements, the yellow line is the model MLD.

4.45.4 Mixed layer depth

The mixed layer depth, MLD, has been calculated within the model using a density criterion, following the definition of Kara et al. (2000) except the reference depth of 10m is changed to 3m, due to the shallower regions of the continental shelf. The MLD is defined as the depth where the density increases, compared to density at 3m depth, corresponds to a temperature decrease of 0.2°C in local surface conditions. The EN4 (Good et al 2013) profile dataset of temperature and salinity was used to calculate an 'observed' Kara mixed layer depth following the same procedure used within the model.

An important point to note here is that on daily/monthly timescales the EN4 dataset is still relatively sparse in the region of interest and often clustered in particular locations. This is particularly true on the continental shelf. Assessing the model as a whole we see a seasonal cycle of errors with small errors in summer/autumn (bias ~10m and RMSD < 25m) and larger errors in winter/spring.

We have therefore also computed the mixed layer depth from the MASSMO4 observations, comparing the mixed layer depth from the gliders (black line Figure 17~~Figure 15~~) with AMM15 and AMM7 in the corresponding locations (yellow line in Figure 17~~Figure 15~~~~not shown~~). AMM15 reproduces the mixed layer depth better than AMM7 and represents the variability of the signal very well. This positive result was also true along the other glider trajectories in this region. AMM15, but not AMM7, also reproduces a deepening in the MLD at the shelf-break. While this could be just a temporary feature, it could also be explained by increased mixing due to internal waves, which begin to be resolved in AMM15, but not AMM7 (Guihou et al. 2017). Graham et al (2018b) also show that the slope current differs between AMM15 than AMM7 in this region, which is likely to affect the water column structure and variability around the shelf-break. Differences in currents are also discussed further in the following section.

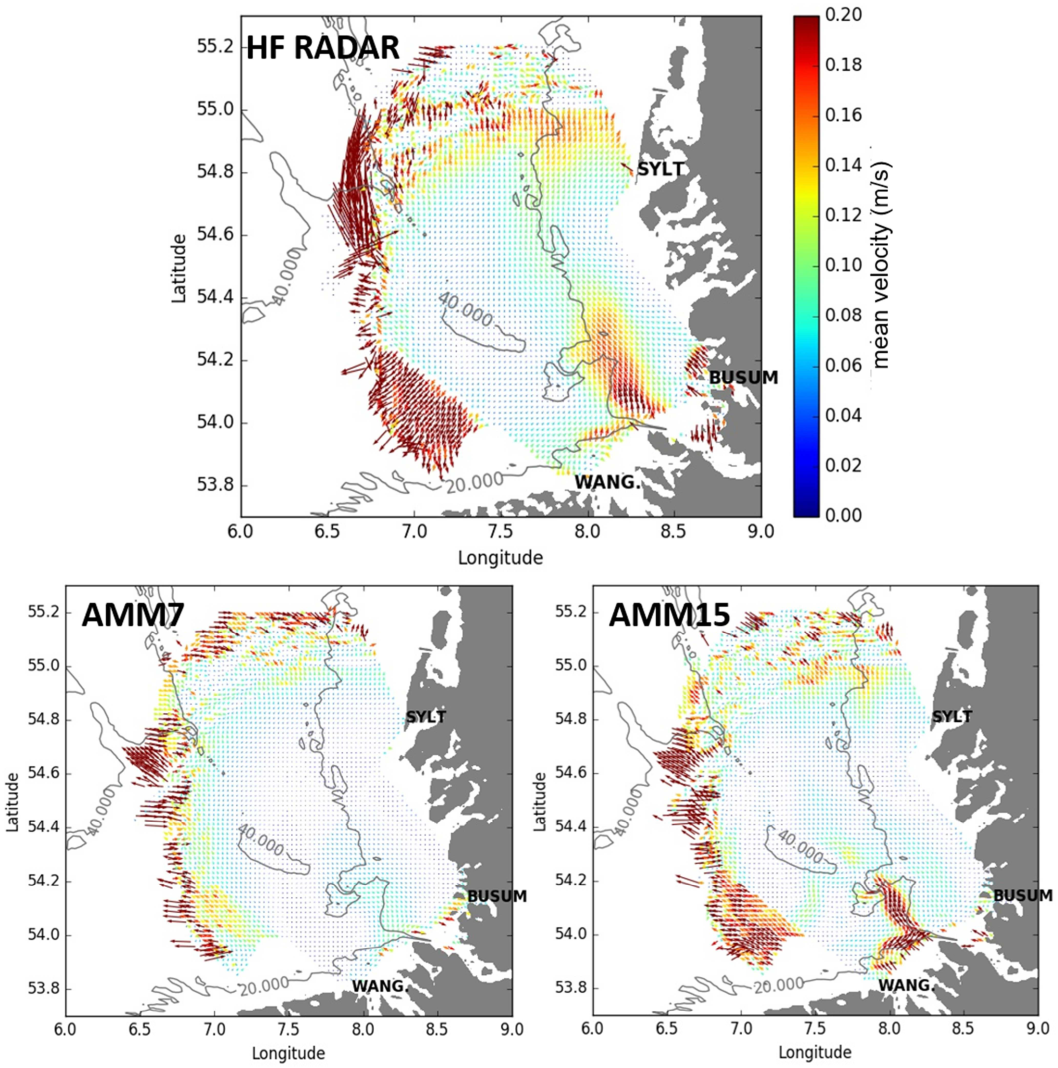
~~4.5 Currents~~

~~A good forecast of the intensity and direction of the currents is needed for operations at sea, but the validation of this variable is particularly difficult due to the scarcity of observations. There are very few measurements of velocity in the model domain. Among the few data available we have decided to use the surface currents measured by the HF radar.~~

~~The HF radar data used here are one month of total surface velocity currents estimated from 3 WERA HF radar systems deployed in the German Bight (Gurgel et al 2011). Data are available through the EMODnet Physics data portal. At the operating frequencies used, the total surface velocities represent an integrated velocity over a depth between 1 and 2m. The HF radar data are averaged every 20 minutes on a grid of resolution of ~3km.~~

~~Because the high frequency variability of the flow in the German bight is dominated by tidal flow, a low pass filter was used to separate the tidal and the residual component of the velocity. Statistics were computed on the high-pass and low-pass filtered velocity components to assess the tidal and residual flow respectively. The assessment of the tidal flow is described in section *4.1.2. Tidal Flow*.~~

~~AMM15 shows a clear improvement, with better defined mean residual surface velocity. In particular, the spatial variability observed in HF radar is better captured by AMM15 than AMM7 (Figure 16). Similar statistics as those estimated for the tidal flow (Figure 6) also show improvement in both amplitude and direction of the residual flow (not shown).~~



~~**Figure 16: March 2017 average surface flow for HF radar (top), AMM7 (bottom left) and AMM15 (bottom right). Model data are re-gridded on the HF radar grid using cubic interpolation. The hourly model output is linearly interpolated every minute to match the HF radar observations. Model output are only plotted where HF radar data are available.**~~

~~The current field of AMM15 is more detailed and seems more realistic than AMM7 but the lack of the observations makes it difficult to properly assess the horizontal velocity field in key areas. Figure 17 represents the surface currents from AMM7 and AMM15 for a single day, to give an example of difference between the two models. AMM15 has a more complex current circulation in the deep part of shelf, with meanders and eddies, not resolved by AMM7. The European slope current, green arrow in Figure 17, is transporting Atlantic water into the North Sea, mainly through the Faroe-Shetland Channel (Marsh at al. 2017), influencing the characteristic of the water in the Northern North Sea and its circulation. The AMM15 current patterns seems more realistic, reproducing eddies and meanders, has shown by drifters measurements done in this area (Burrows et al. 1999). The European slope current plays a major role in the across shelf transport, with AMM15 better reproducing the water exchanges as described in Graham et al 20018b.~~

~~The two models are also very different in the area characterised by the Norwegian Coastal Current (NCC) which is highlighted by the yellow vectors in Figure 17.~~

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~~The NCC is a coastal current flowing from Skagerrak to the Barents Sea, following the Norwegian coastline, in the upper layer (50-100m) over the Norwegian Trench. This current is characterized by a front between low salinity water coming from the brackish Baltic sea and Norwegian coastal water, and the Atlantic water. This current has mesoscale meanders and eddies (Ikeda et al. 1989) propagating northward along the Norwegian coast. AMM15 reproduces better the mesoscale eddies and meanders of the NCC which are not resolved by AMM7.~~

~~The Scottish coastal current, seems to be well resolved by AMM15, with a strong current flowing along the west Scottish coast and meandering before entering the channel between mainland Scotland and the Hebrides (the Minch). This is a persistent current that interacts with the island chain of the Hebrides (Simpson 1986). AMM15 has a more detailed coastline and bathymetry in this area which is likely to be one of the main reasons why the model resolves this current. In AMM7, this current is almost absent, or too weak and misplaced to the west, instead of being, as it in AMM15, between the islands and the mainland (Figure 17, red arrows). The contrast between the low salinity along the coast and the higher salinity of the Atlantic water is another key driver of this current (Simpson 1986), and this is better represented by AMM15, which has an improved salinity field compared to AMM7. AMM15 seems to be much less diffusive in the proximity of the river plumes keeping a narrower plume close to the coast and has a lower lateral diffusion (Graham et al. 2018a). AMM7 has low salinity water (less than 34.5 PSU) spreading much further away from the coast, all the way to the Outer Hebrides, while the salinity gradient in AMM15 is located between the Minch and the western side of the Outer Hebrides. This assessment shows that AMM15 is in very good agreement with literature in this area. Further studies, and possibly targeted observations, are needed to validate this preliminary result and to assess AMM15 skills in predicting the seasonal variability of this current and the other currents described in this study.~~

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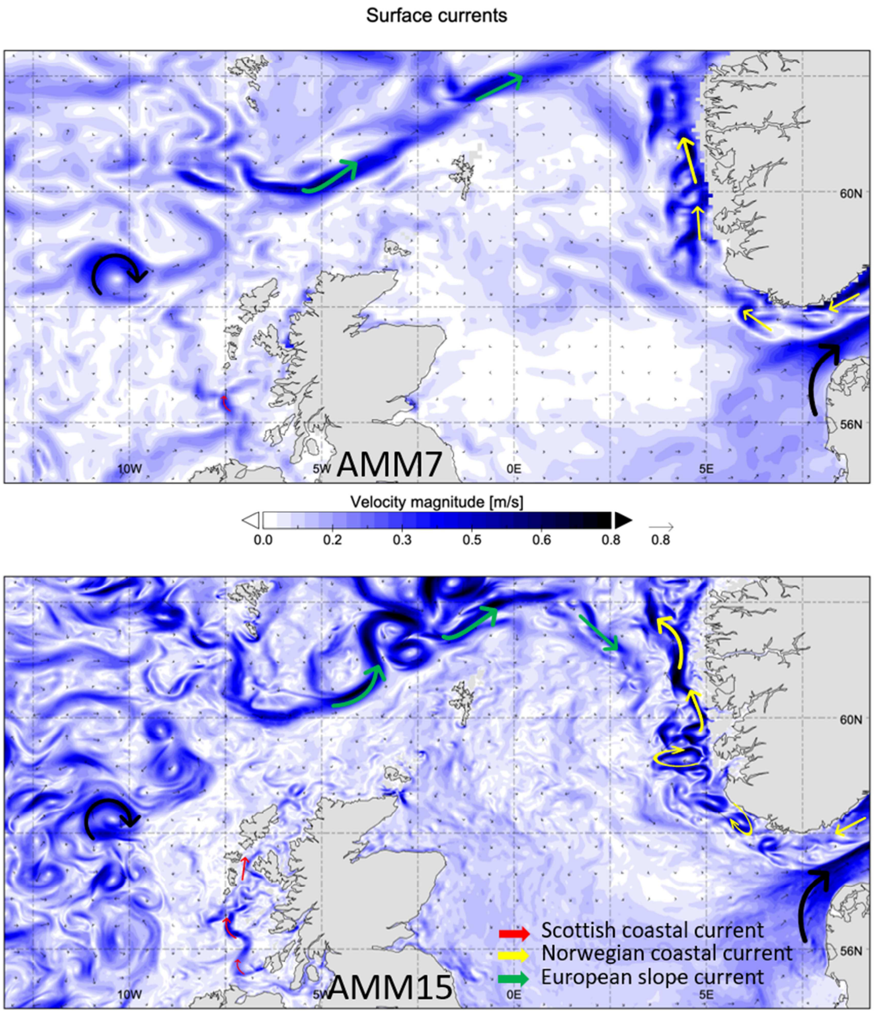

~~Figure 17: Surface current from AMM7 (top) and AMM15 (bottom), daily mean 02-12-2018.~~

5 Conclusions and future developments

The validation of pre-operational trial experiments for a new 1.5km resolution model of the European North West Shelf, against observations and the predecessor 7km system, shows positive results.

AMM15 has improved skill compared to AMM7 and has proven to be an improvement especially when compared to high spatial/te~~i~~mporal resolution observations. The ~~currents~~ pattern and variability of surface currents are better reproduced by the new system, with improved temperature and salinity throughout the whole water column. The most outstanding improvement seems to be in the salinity which is closer to observations at basin scale and locally. Probably there are different factors which contribute to this improvement. Firstly, salinity will be impacted by river runoff. While the two models have a similar daily climatological river runoff data set it could differ locally. Despite similar runoff, the path of the river plume may also differ in the two models, so may lead to local changes in salinity, for example in the German Bight, where the plume stays close to the coast rather than diffusing off-shore. Secondly, the Atlantic and Baltic boundaries are in a different geographical location and this could imply differences in the fluxes at the boundary. There is a strong salinity variability at the Baltic boundary and this can strongly influence the salinity field and variability in the North Sea. There are ongoing developments to improve the Baltic boundary implementation in AMM15 that will help to understand further the impact of this boundary on the NWS. The Atlantic boundaries influence the exchange across the shelf and they could be partly responsible for improvements like those shown in the north of Scotland where the model has been compared with glider data and the AMM15 salinity field is much more realistic than AMM7. The significant improvement in this area could also be due to AMM15 better resolving the flow through the Faroe-Shetland Channel and shelf-break exchange. The work from Graham et al. 2018b, shows that there is an increased flux across the shelf-break in AMM15 compared to AMM7. This could affect the exchange of water masses around the shelf break, and therefore influence salinity on the shelf. Another reason could be the differences in the atmospheric forcing with the two models forced by a different Evaporation-Precipitation rate. As stated earlier, further studies will be carried out to properly assess the impact of the ECMWF forcing compared to the Met Office forcing.

The assimilation scheme used in AMM15 is broadly unchanged from that used in AMM7. While the short correlation length-scale is now ~5km (compared to ~20km), the observation and background error covariances, and the observation types assimilated, remain unchanged. In this initial implementation of AMM15 we have not attempted to improve the use of observations in the assimilation scheme. We are currently investigating how to adapt our assimilation scheme to assimilate SLA observations in stratified water and will be re-estimating the observation and background error covariances for this new higher resolution system.

The 1.5 km resolution model provides a better representation of dynamical features such as coastal currents, fronts and mesoscale eddies that can vary in size from only a few kilometres in shelf-seas to tens of kilometres, but a proper assessment is very difficult due to the high variability of these patterns and the very limited number of available observations.

The users' benefit, using the newly improved European shelf product AMM15, will vary depending from their applications. A positive impact on the users and their application is expected from AMM15 products. Higher resolution currents fields with an improved representation of the coastal areas should improve the results of applications like drifting models simulating pollutant or oil spill dispersion and all the applications that need a high resolution currents field. All the acoustic applications, strongly depending on the density stratification and its variability, will benefit from these new products since they have a better representation of the water masses. A general positive impact is expected for most of the users like public bodies responsible for marine environmental regulation, aquaculture industries, marine renewable oil and gas industries."

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There are some improvements in the tidal signal in AMM15 even if not so remarkable as with the salinity. One limitation is the minimum depth set to 10m that prevents the model from properly taking into account the shallow bathymetry in the coastal areas. A wetting and drying implementation in under development~~s~~ and ~~could help~~ could help to have a more realistic bathymetry, with improved tidal signal in very shallow waters, in a future version of AMM15.

~~The~~ AMM15 ~~ocean~~ has been developed with coupled prediction in mind, the domain matching that of the Met Office atmospheric model UKV. Regional coupled model developments have been done and coupled ocean forecasting systems are already planned.

The AMM15 system described in this paper, has been already tested in an ocean-wave coupled configuration (Lewis et al. 2018a) which is planned to become operational in 2020. We hope to add the biogeochemical components in a few years, but a precise plan is not yet available. Indeed, a preliminary version of AMM15 with coupled ocean-biogeochemistry is under development with ~~first~~ encouraging initial results but is still far ~~away~~ from meeting ~~the~~ operational requirements. A coupled ocean atmosphere version of this model has ~~been~~ already been developed for research, Lewis et al. 2018b and studies will continue toward a fully coupled prediction system with ocean, atmosphere, land and wave model.

Acknowledgements

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