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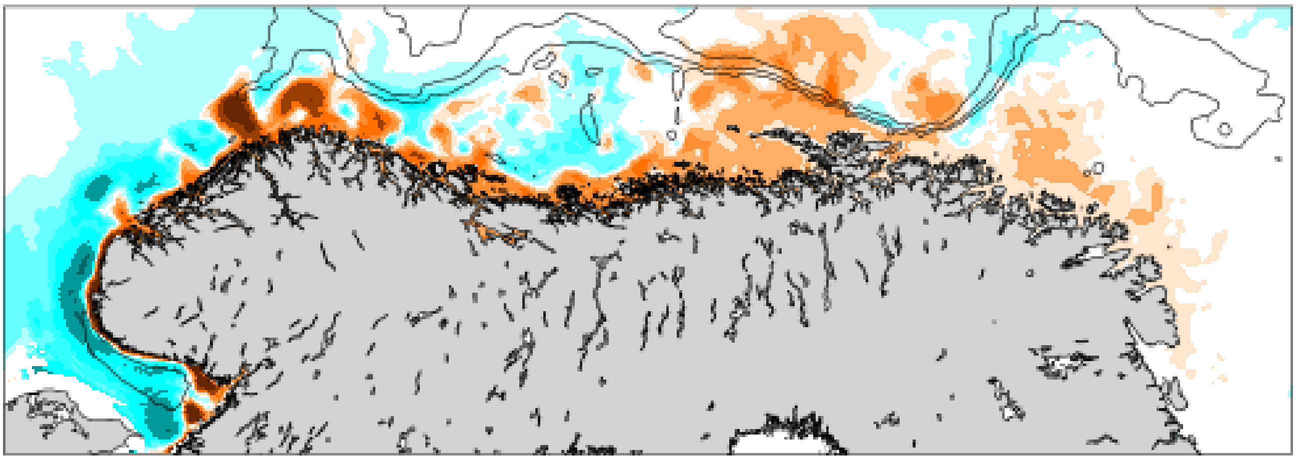

Evaluation of open boundary conditions in ROMS

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Norwegian Meteorological Institute

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Abstract

Results from the operational model for ocean circulation in Norwegian coastal waters, *NorKyst-800m*, have been compiled on a daily basis since 2012-06-27. The results for salinity and temperature have been compared to cruise data that are available from the Institute of Marine Research (Norway). Generally, the results have a slight cold bias of a few tenths of a degree, and a strong, positive salinity bias of 0.5 – 2 PSU. The purpose of the present study is to examine the role of open boundary conditions (OBCs) for the biases, with a focus on the salinity bias. A set of three 1-year long experiments have been run, differing in the choice of OBCs. We find that the various experiments give contrasting results for salinity, but also to some degree the ocean temperature distribution and the eddy kinetic energy. We conclude that using OBCs from a different source than in the present operational set-up will likely improve the quality of the model results. Our recommendation is that an alternative configuration to today's operational *NorKyst-800m* is implemented and run in parallel. When the new implementation is stable and is found to exhibit the improvements that are reported here, this implementation should be the base for future development of the *NorKyst-800m* configuration. At some point, a complete substitution of today's operational configuration with the recommended alternative should also be considered.

Keywords

Oceanography, modeling, coast, open boundary conditions

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Abstract

Results from the operational model for ocean circulation in Norwegian coastal waters, *NorKyst-800m*, have been compiled on a daily basis since 2012-06-27. The results for salinity and temperature have been compared to cruise data that are available from the Institute of Marine Research (Norway). Generally, the results have a slight cold bias of a few tenths of a degree, and a strong, positive salinity bias of 0.5 – 2 PSU. The purpose of the present study is to examine the role of open boundary conditions (OBCs) for the biases, with a focus on the salinity bias. A set of three 1-year long experiments have been run, differing in the choice of OBCs. We find that the various experiments give contrasting results for salinity, but also to some degree the ocean temperature distribution and the eddy kinetic energy. We conclude that using OBCs from a different source than in the present operational set-up will likely improve the quality of the model results. Our recommendation is that an alternative configuration to today's operational *NorKyst-800m* is implemented and run in parallel. When the new implementation is stable and is found to exhibit the improvements that are reported here, this implementation should be the base for future development of the *NorKyst-800m* configuration. At some point, a complete substitution of today's operational configuration with the recommended alternative should also be considered.

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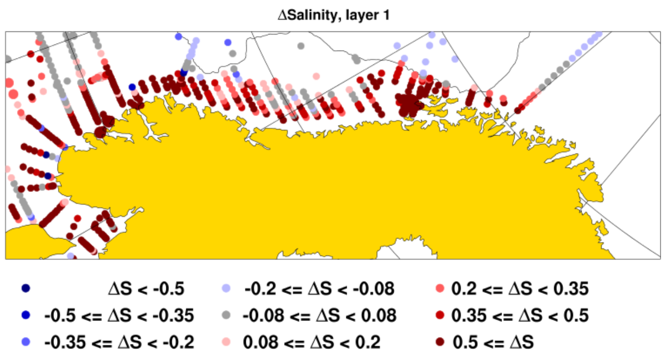

Figure 1: Validation results for salinity, using cruise data available from IMR and model results from *NorKyst-800m*. Shown here are results for the upper 5 m, for the second quarter (Apr-May-Jun) of 2016.

1 Introduction

The Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams , 2005) has been used at the Norwegian Meteorological Institute (MET Norway) for operational forecasts, hindcast studies, regional ocean climate studies and in applications such as oil spill simulations, drift of objects, spread of harmful algae and salmon lice; see e.g. Albretsen et al. (2011), Albretsen (2009), Røed and Kristensen (2013), and Melsom et al. (2009)). Much of this work has been performed in collaboration with the Institute of Marine Research (IMR) in Norway.

The validation results of the operational *NorKyst-800m* ROMS configuration is visualized here. These validation results are updated monthly, and are aggregated on quarterly and annual bases. An example is displayed in Figure 1.

We have found that this model has a positive salinity bias, particularly in the region of the Norwegian Coastal Current. Several features of the configuration can conceivably give rise to this problem:

- excessive mixing of salt
- impeded river run-off
- error(s) in the implementation of surface fresh water flux
- non-conserving numerical schemes

However, an additional, potential source for the salinity problem is the topic of the present investigation. We have noted a similar problem in the results from another ROMS implementation that is included in the operational system for ocean circulation forecasting at MET Norway, which is referred to as the *Nordic-4km* configuration. Moreover, this is the model that provides conditions along the open lateral boundaries of *NorKyst-800m*.

We also note that the two configurations also share an issue regarding temperature biases, namely a cold bias in the surface layer over the abyssal Norwegian Sea, which for both configurations is largest during winter.

In response to the discrepancies described above, we have performed a set of three 1 year simulations with *NorKyst-800m* which differed only in the choice of model used for providing the open boundary conditions (OBCs). The experimental set-up is described in Section 2. The results of the experiments are analyzed in Section 3, and our recommendations regarding possible modifications in the *NorKyst-800m* configurations are given in Section 4.

2 Configuration of experiments

2.1 ROMS Norkyst-800m

The Regional Ocean Model System (ROMS) is a hydrostatic, primitive equation ocean circulation model. The model is formulated in a vertical s-coordinate in which the layers are draped over the terrain. The s-coordinate is a generalized sigma-coordinate, amended to support a weighted distribution of the layers with depth. An increase in vertical resolution can be gained either near the free sea surface, ocean floor or both. This allows for a more detailed description of the processes occurring in the region(s) of enhanced resolution. While this is one of the model's strengths, the number of layers and the degree of stretching needs to be chosen with care. This is due to an error related to the computation of the pressure gradient, arising in models with this type of vertical coordinate.

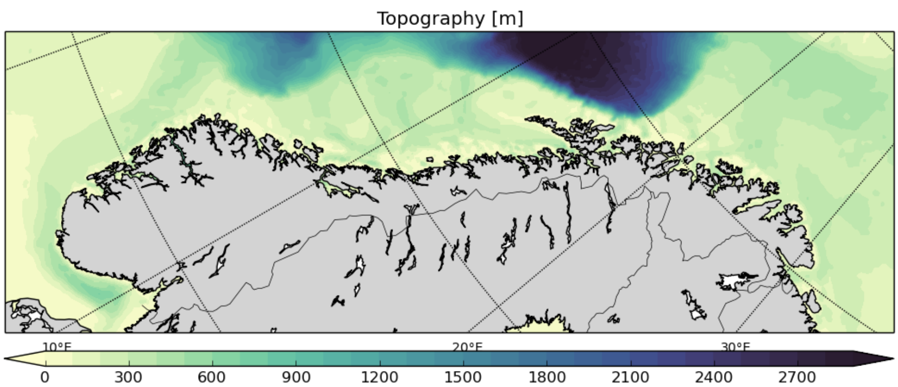

Figure 2: Bottom topography in the *NorKyst-800m* configurations from which results are examined here.

In our conducted experiments, the configuration of the 902×2602 horizontal grid is inherited from the *NorKyst-800m* model setup of Albretsen et al. (2011). The model domain is depicted in Figure 2. With a nominal grid spacing of 800m, the model is considered a so-called eddy-resolving model. This implies that mesoscale variability, such as oceanic storms, to a large extent is represented in the model, as opposed to parameterized. In the vertical, the grid consists of 35 layers. The distribution of the layers is stretched in order to obtain a finer resolution near the surface, with nearly no extra gain in the resolution near the bottom. The stretching parameters are set to $\theta_s = 6,\ \theta_b = 0.1,\ h_c = 100$m, where θ_s and θ_b denotes the degree of stretching within the upper and lower 100 meters of a water column. In an attempt to alleviate some of the pressure gradient error, the vertical stretching at the surface, θ_s, is somewhat reduced from the *NorKyst-800m* model setup in Albretsen et al. (2011). An example of the layer partition along a transect off the Norwegian coast is shown in Figure 3.

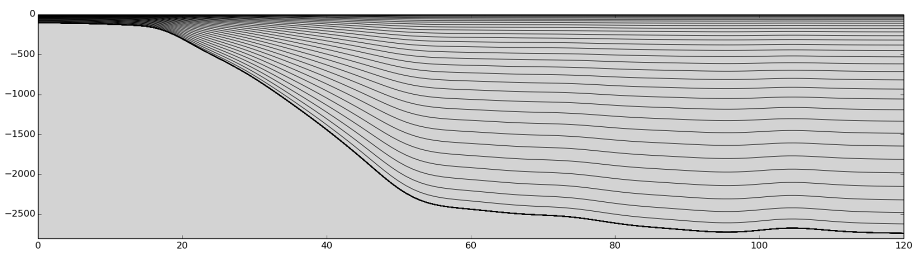

Figure 3: Sample transect showing the layer partitioning in *NorKyst-800m*.

We use a a fourth-ordered centered scheme for vertical advection, and a third-ordered upwind scheme for horizontal tracer and momentum advection which acts to reduce spurious mixing. No explicit horizontal eddy viscocity or diffusion is applied, as this is implicitly present in the advection scheme. The k-epsilon version of the General Length Scale(GLS) scheme (see Umlauf and Burchard (2003) and Warner et al. (2005)) is employed for subgrid-scale vertical mixing.

None of the aforementioned model options were changed in the three experiments (specified in section 2.2). However, in terms of boundary conditions and model version, the last experiment differ from the other two. The two first simulations were run with ROMS version 3.5, while simulation 3 was run with ROMS version 3.7. The newer code offer, amongst other things, two new boundary conditions. In simulation 3, the Implicit Chapman boundary condition for the free surface and the Flather condition for 2D momentum, were changed to the new Explicit Chapman and Schepetkin boundary conditions. The latter combination has been considered more stable and providing less artificial reflections at the boundary. The Radiation conditions were kept for the 3D velocities and hydrography.

SIMULATION PERIOD	2014.07.01 - 2015.30.06
MODEL	
Experiment 1,2	ROMS v3.5
Experiment 3	ROMS v3.7
HORIZONTAL RESOLUTION	800m $\times$ 800m
VERTICAL LAYERS	# 35
VSTRETCHING	2
VTRANSFORM	2
θ_s	6.0
θ_b	0.1
HORIZONTAL ADVECTION	3rd ordered upwind
VERTICAL ADVECTION	4th ordered centered
PARAMETRIZATION OF TURBULENT MIXING	Generic Length Scale

Table 1: Details regarding the model setup. Note that conditions at the open boundaries is discussed in Section 2.2 below.

2.2 Boundary conditions

All simulations were conducted with 2-hourly atmospheric forcing from the Norwegian Reanalysis Archive (NORA) (Reistad et al. , 2011). This is a regional downscaling of results from the European Reanalysis project (ERA-40/ERA interim, see Uppala et al. (2005)). NORA is a 10 km resolution product which includes assimilation of regional observations.

Conditions at the lateral open boundaries were prescribed as daily mean values for surface elevation and depth varying ocean currents, temperature and salinity. These results were acquired from a set of three ocean circulation simulations:

1. *ROMS Nordic-4km*, the in-house model presently used to provide OBCs in the operational *NorKyst-800m* configuration; hereafter referred to as *RN4*. This is a regional model that is nested into a larger basin scale model with 20 km horizontal resolution. Results are available for 17 depths above 3000 m: 0, 3, 10, 15, 25, 50, 75, 100,

150, 200, 250, 300, 500, 700, 1000, 2000, 3000 (in m)

2. *CMEMS-ARC TOPAZ*, the Copernicus Marine Environment Monitoring Service (CMEMS) model for the Arctic region (Sakov et al. , 2012); hereafter referred to as *C-ARC*. This is a hemispheric model with climatologies applied at the boundaries in the south Atlantic and in the Bering Strait. Results are available for 12 depths above 3000 m: 5, 30, 50, 100, 200, 400, 700, 1000, 1500, 2000, 2500, 3000 (in m)

3. *CMEMS-GLO FOAM*, the CMEMS global model from UK Met Office (MacLachlan et al. , 2015); hereafter referred to as *C-GLO*. Results are available for 37 depths above 3000 m: 0, 5, 10, 15, 20, 25, 30, 40, 50, 60, 75, 100, 125, 150, 175, 200, 225, 250, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1750, 2000, 2250, 2500, 2750, 3000 (in m)1

We will subsequently refer to this set as the “OBC models”.

Higher frequency dynamic forcing was included by incorporating tidal elevation and currents from the TOPEX/POSEIDON tides estimates (TPXO) (Egbert et al. , 1994). River run-off were supplied as daily values for 250 rivers (J. Albretsen, *pers. comm.*).

Thus, a set of simulations with three *NorKyst-800m* configurations were performed, differing only in the choice of OBCs. Results from the three different simulations are analyzed, compared to each other, and compared to observations in Section 3 below. Hereafter these simulations will be referred to as *NK-NORDIC*, *NK-ARC* and *NK-GLO*, respectively. The set of simulations will be referred to as the “OBC experiments”.

3 Results

3.1 Contrasts between results from the OBC models

We study how differences in OBCs from the set of OBC models lead to contrasting results. As described in Section 2.1, all of the OBC experiments are initialized with results from *C-GLO*. Hence, experiments *NK-ARC* and *NK-NORDIC* use OBCs that initially do not match the interior domain. Consequently, it will take some time for these two experiments to equilibrate.

To get a first impression of the contrasts between the results from the OBC models, the monthly averaged offsets from the reference OBC model *C-GLO* for salinity and temperature are displayed in Figure 4 and Figure 5, respectively.

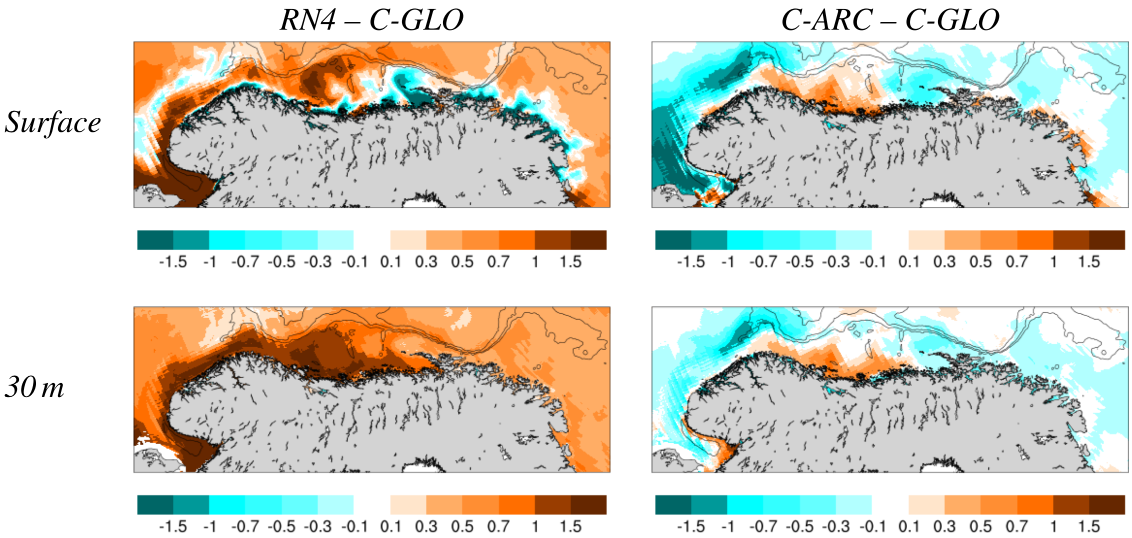

Figure 4: Differences in salinity results from the OBC models interpolated to the *NorKyst-800m* domain, with results from *C-GLO* as reference (mean values from 2014-07). Left and right column display offsets for *RN4* and *C-ARC*, respectively. Top and bottom row show differences at the surface and at the 30 m level, respectively.

From Figure 4, we note that *RN4* is generally higher in salinity than *C-GLO*, and this is also true at the open boundaries. On the other hand we see that salinities in *C-ARC* are much more similar to *C-GLO*, although there are som regional differences. Moreover, differences along the open boundaries are relatively modest in this latter case.

Figure 5 reveals that in July 2014, *C-GLO* is the coldest of the three OBC models at the surface. This is in stark contrast to the differences at the 30 m level, where *C-GLO*

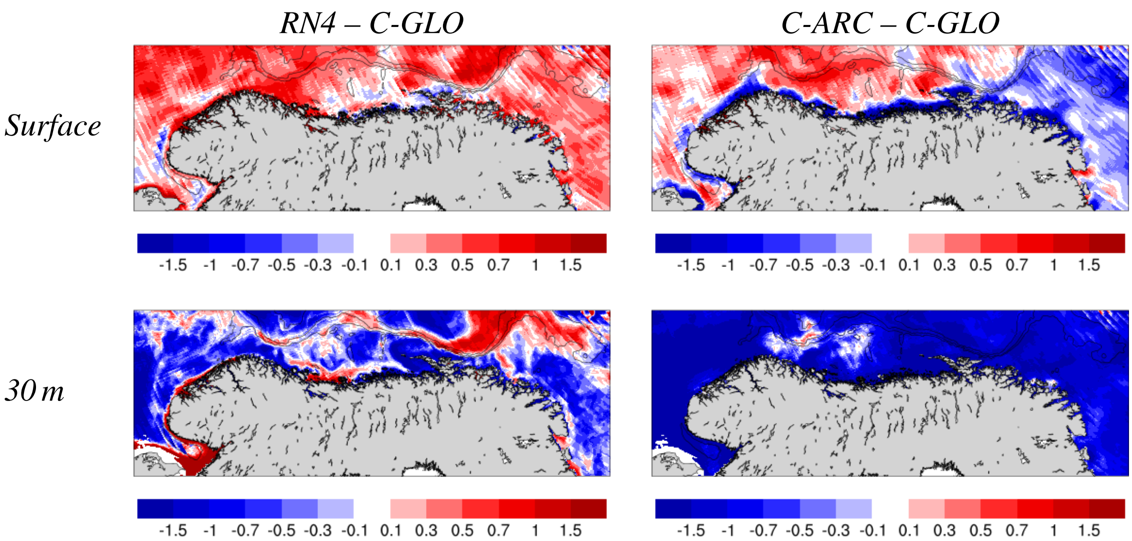

Figure 5: As Figure 4, but for differences in temperature.

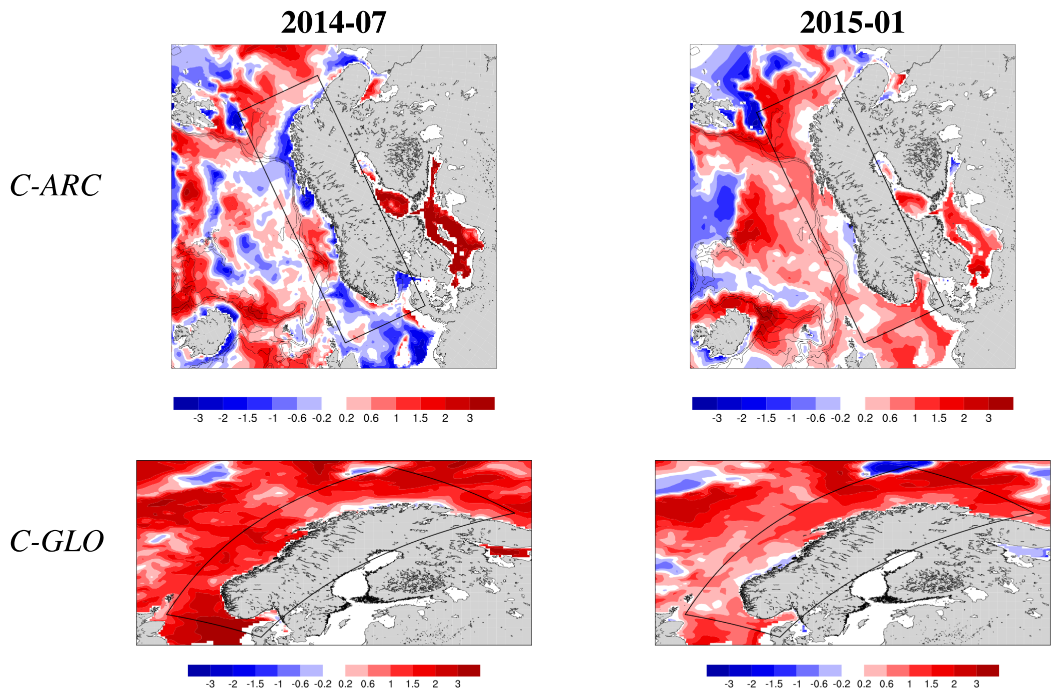

Figure 6: Deviations of monthly means in two of the OBC models from correspond WOA monthly data, for temperature at 30 m. Top and bottom rows show differences for *C-ARC* and *C-GLO*, respectively. Differences during summer (July) and winter (January) are displayed in the left and right columns, respectively. The *NorKyst-800m* domain is indicated by black lines in all panels.

is generally the warmest. Hence, for this month the vertical temperature distribution is much more uniform in *C-GLO* when compared to the other two OBC models.

The temperature difference at 30 m, as displayed in the bottom left panel of Figure 5 has a magnitude that leads us to further investigate this issue. To better understand if one or both of *C-ARC* and *C-GLO* are realistic, we compare the monthly averages at this level with the World Ocean Atlas (WOA) data (Locarnini et al. , 2010) for the same calendar month. The results are displayed in Figure 6.

From Figure 7, we find that the summer temperatures at 30 m depth is much higher in the *C-GLO* results than in the WOA climatology, with typical differences of around 2 K in the *NorKyst-800m* domain. During winter, both of these OBC models are warmer than the climatology in this domain. The results for the 50 m level, and results for 2015-07 (neither displayed here) are similar to what is shown in Figure 7.

3.2 Evolution in results from OBC models

Next, we briefly look at how the OBC models evolve over the present 12 month simulation period, as revealed from the monthly averaged interpolated to the *NorKyst-800m* domain.

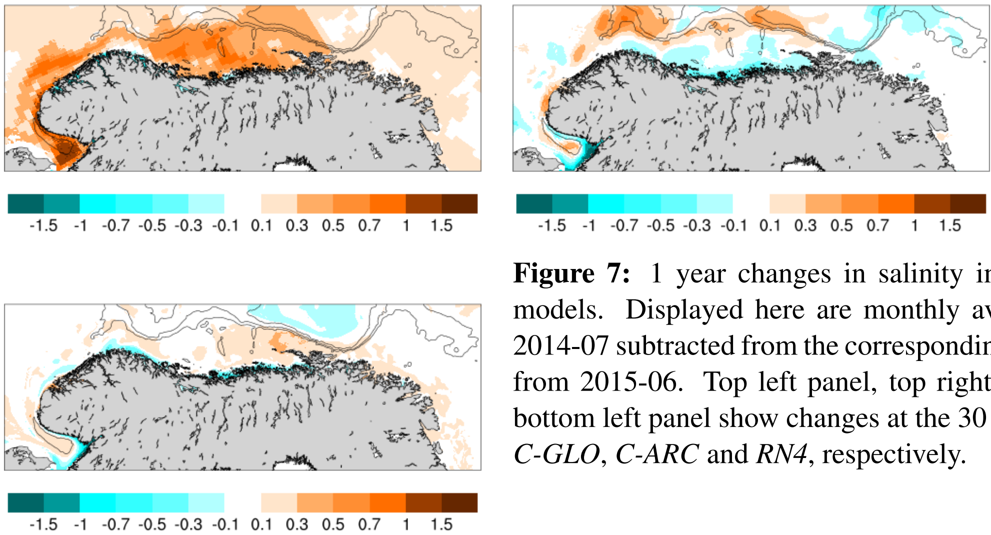

Figure 7: 1 year changes in salinity in the OBC models. Displayed here are monthly averages for 2014-07 subtracted from the corresponding averages from 2015-06. Top left panel, top right panel and bottom left panel show changes at the 30 m level for *C-GLO*, *C-ARC* and *RN4*, respectively.

This comparison is included in order to provide information of the magnitude of changes that can be expected in the OBC experiments.

We consider the changes from 2014-07 to 2015-06. Displayed in Figure 7 are changes in salinity in the three OBC models at the 30 m level. We find that while the salinity in *C-GLO* generally increases, little change is seen in the evolution in results from *RN4*. In the results from *C-ARC*, there are modest regional changes, with increasing salinities in the region of the Norwegian Atlantic Current.

The temperature at 30 m is lower in 2014-06 than in 2015-07 in all of the OBC models, by about 1 K (not shown). This is likely due to the seasonal cycle in this region, as near-surface water masses reach their highest temperatures in the late summer.

3.3 Spin-up of the OBC experiments

Here, we examine the development of the OBC experiments, in order to identify the period when the three experiments have reached a state that justifies comparison. The kinetic energy level is a property that can be used to evaluate if an experiment has transitioned from an initial state which is usually smooth to a state in which the circulation properly responds to the applied forcing. In a domain of the size of *NorKyst-800m*, the kinetic energy should equilibrate within a month or two. However, the present set of experiments differ in the application of a set of OBCs that is applied.

Hence, the response to the time-space distribution of temperature and salinity at the open boundaries is of particular interest for the present study. Since one of the OBC experiments takes its initial conditions and OBCs from the same OBC model (*C-GLO*),

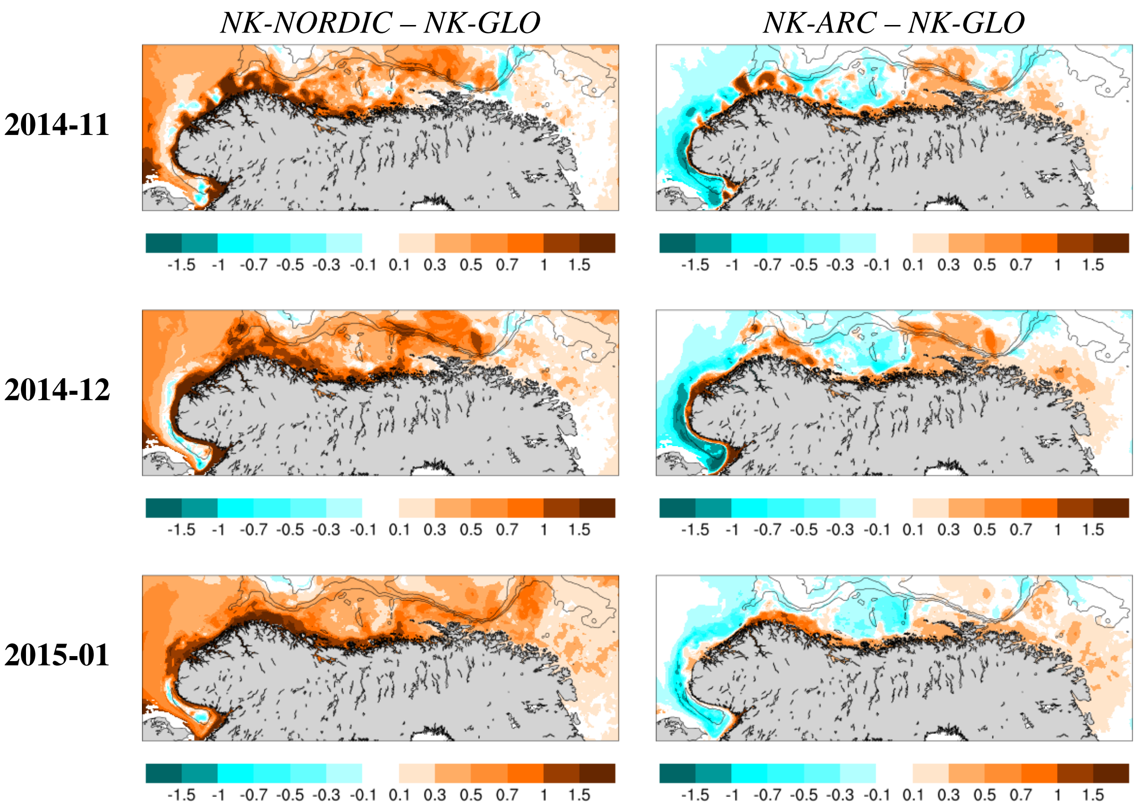

Figure 8: Differences in monthly averaged results for salinity at the 30 m level, for three consecutive months. Left column panels display differences between results with *NK-NORDIC* (OBCs from *RN4*) and *NK-GLO* (OBCs from *C-GLO*). The panels in the right column show the corresponding differences between *NK-ARC* (OBCs from *C-ARC*) and *NK-GLO*.

while the others uses a mix, it is not obvious when all experiments have reach states that allows for a fair comparison. In order to examine when the results from the OBC experiments are ripe for comparison, we look at the evolution of the salinity differences at 30 m, displayed in Figure 8.

We expect the differences to saturate at the latest in the northernmost region (to the right in the panels in Figure 8), since this is the down-stream area of the two main currents (the Norwegian Coastal Current and the Norwegian Atlantic Current) in this region. From Figure 8, we see that our presumption holds. Moreover, we conclude that with a possible exception of the part of the *NorKyst-800m* domain that extends into the Barents Sea, the differences have reached a saturated state in 2015-01.

3.4 Contrasts between results from the OBC experiments

Contrasts between results from the set of OBC experiments were partly investigated in the previous sub-section (Figure 8). Here, we seek to reach a qualitative description of

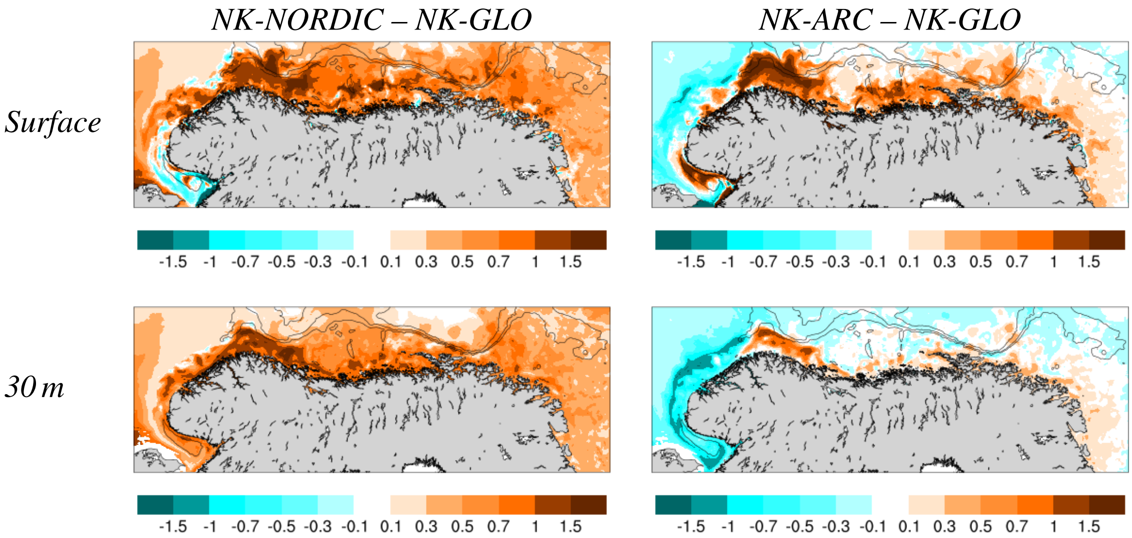

Figure 9: Differences in monthly averaged results for salinity during 2015-06. Panels in the top and bottom rows correspond to differences at the surface and the 30 m level, respectively. Columns are arranged as in Figure 8.

differences between the set of OBC experiments. We choose to inspect the results from the final simulation month for this purpose, i.e., 2015-06.

It is of considerable interest to compare these results to the corresponding results from the OBC models, because such a comparison provides essential information about the impact of OBCs on the high-resolution simulations with the *NorKyst-800m* configuration. The differences between the OBC models in 2015-06 are very similar to those depicted for 2014-07 in Figures 4 and 5. For reference, the differences in the OBC models for 2015-06 are displayed in Figures A1 and A2 in the Appendix.

Contrasts in results at the 30 m level between the OBC experiments (lower panels in Figures 9 and 10) are very similar to the corresponding differences between the results from the OBC models (lower panels in Figures A1 and A2). The main change is that the difference between results based on *RN4* and on *C-GLO* are somewhat reduced in the OBC experiments. We conclude that the choice of lateral boundary conditions dominate the results for hydrography one year into the high resolution simulation.

At the surface the contrasts differ more than at the 30 m level (upper panels in the same set of figures). This is likely due to the impact of surface forcing. While all of the OBC experiments receive their surface forcing from the same atmospheric reanalysis (NORA, see Section 2.2 for details), none of the OBC models were forced with NORA. Furthermore, there are also differences in the river run-off that have been applied in the

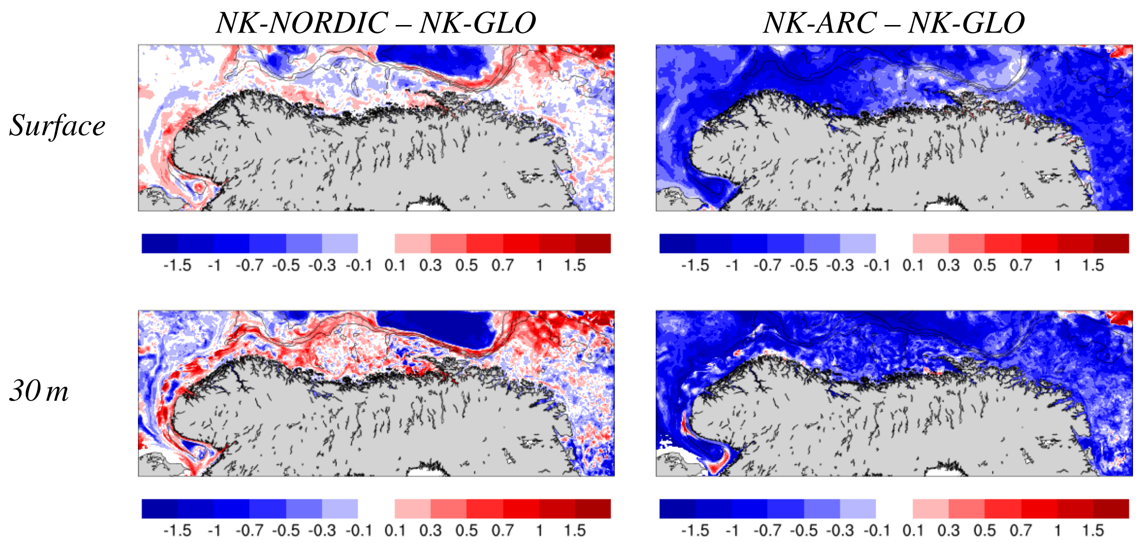

Figure 10: As Figure 9, but for differences in temperature.

OBC experiments on one hand, and the OBC models on the other. Nevertheless, there are large differences beween results from the individual OBC experiments. Hence, the lateral boundary conditions play a significant role at the surface as well as their dominating role in the water masses below.

Next, we examine the results for temperature. It is evident that the *NK-ARC* simulation exhibits the largest contrasts when pairing up the results from the OBC experiments (Figure 10). *NK-ARC* is considerably colder than the other two OBC experiments. There are indications that these contrasts in temperature is changing somewhat with seasons, as the surface waters of the Norwegian Coastal Current off southern Norway is actually warmer in *NK-ARC* than in *NK-GLO*. Finally, we note that in the Lofoten Basin (the deep ocean off the Lofoten archipelago), *NK-NORDIC* is colder than *NK-GLO* (not easily seen with the choice of color scale in Figure 10).

3.5 Comparison with observations

We compare the results for temperature and salinity from the OBC experiments with observations from cruise data that are available from IMR. This is done using the same methodology and software that is implemented for montitoring the quality of the operational *NorKyst-800m* configuration. From Figure 1 we know that there is a distinct positive salinity bias in these operational results.

Hence, we start this investigation by examining the salinity biases in the OBC experiments. These biases are depicted for the first 6 months in 2015 in Figure 11. We find

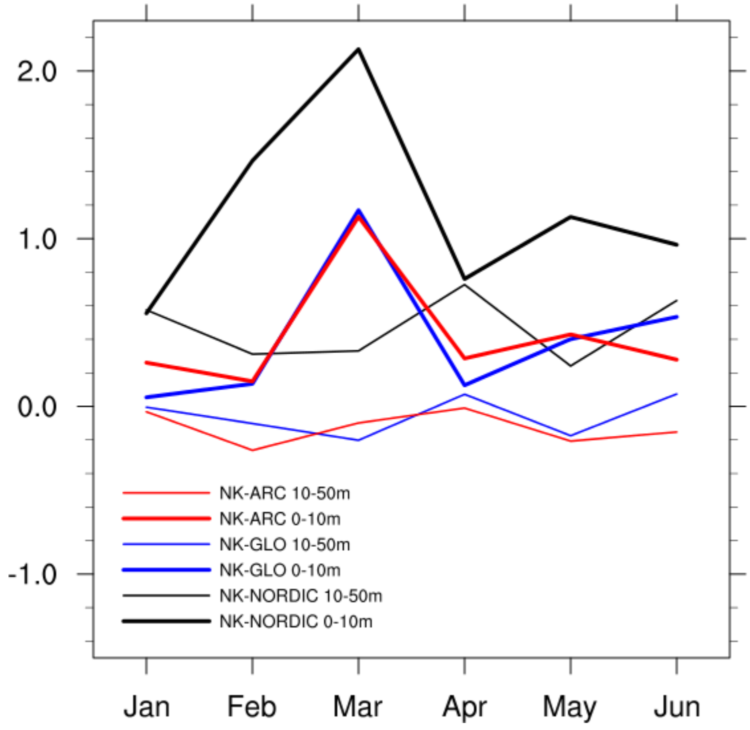

Figure 11: Salinity bias in the OBC experiments for calendar months in 2015. Model results are compared to cruise data from IMR, with positive values when model salinities are higher than observations. Thick and thin lines corresponds to model-observation comparisons for the layers 0–10 m and 10–50 m, respectively.

that the *NK-NORDIC* experiment has large positive salinity biases. This is not surprising, since this is the experiment which is most similar to the operational configuration.

For the other two OBC experiments, the salinity biases are substantially reduced. This is according to expectations, since both of the corresponding OBC models have lower salinities than the *RN4* model (see Figure 4). Judging by the biases, *NK-GLO* and *NK-ARC* seem to perform with similar quality for salinity.

The temperature biases are displayed in Figure 12. We find that during winter *NK-ARC* has a cold bias of about 0.5 K, while the other two OBC experiments have much smaller biases. However, as summer approaches, the situation reverses, with *NK-ARC* becoming warmer than the other two in the upper 10 m og the water column, and has lower biases than *NK-GLO* in June. The lack of results for all seasons makes it difficult to compare the quality of results for temperature from the OBC experiments. Nevertheless, we note that for the months for which validation results for temperature are available, the biases in *NK-GLO* exhibit the lowest month-to-month variability.

The observations are not uniform in time and space, so differences from one month to another are likely to be impacted by sampling variability. The sampling of the waters in the Norwegian Coastal Current has the best geographical coverage towards the end of the simulated period. Hence, we decide to examine results from the second quarter (April-May-June) more closely.

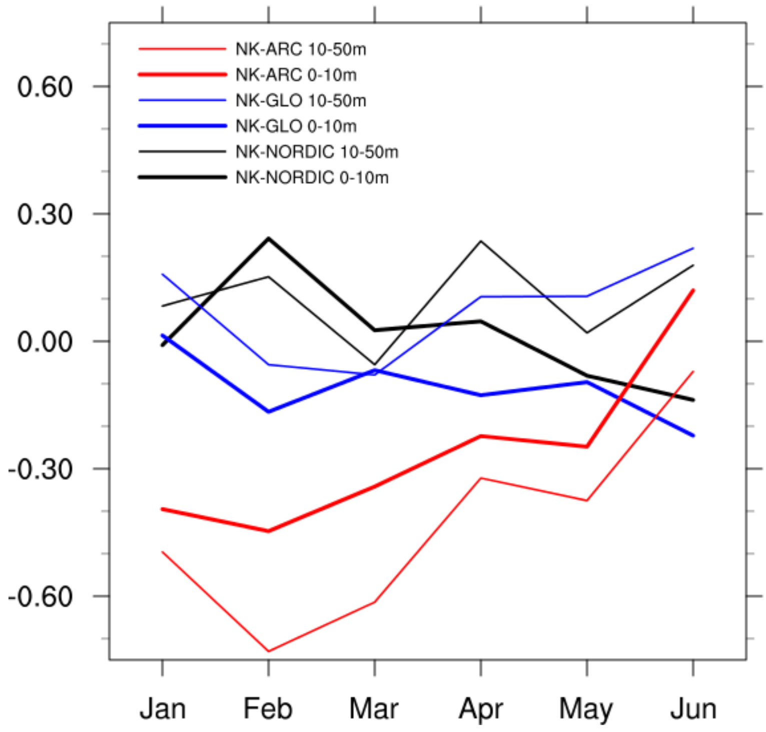

Figure 12: As Figure 11, but for temperature.

In this context, we point out that the time distribution of sampling is significantly skewed towards the first month of this quarter:

- 2015-04 observations: 351 for temperature / 351 for salinity
- 2015-05 observations: 114 for temperature / 59 for salinity
- 2015-06 observations: 23 for temperature / 23 for salinity

Maps presenting the model-observation offsets of temperature and salinity for the 10–30 m layer are shown as Figure 13. We find that *NK-GLO* and *NK-ARC* both compare favorably with the observations of temperature that are closest to the coast. A bit farther off-coast, *NK-GLO* has a slight warm bias in the south, whereas *NK-ARC* has a cold bias in the north. *NK-NORDIC* has a strong cold bias in the Lofoten Basin, elsewhere this experiment has offsets in temperature that are similar to the other OBC experiments.

When considering the results for salinity in Figure 13, the outcome of *NK-NORDIC* proves to have the same issue of being much too high in salinity as we find in the operational configuration (see Figure 4). For the remaining two OBC experiments, we find that the picture is quite mixed, and neither of the two is clearly emerging as the most accurate simulation. They both have a tendency of being a bit high in salinity for the Norwegian Coastal Current, and a bit low outside.

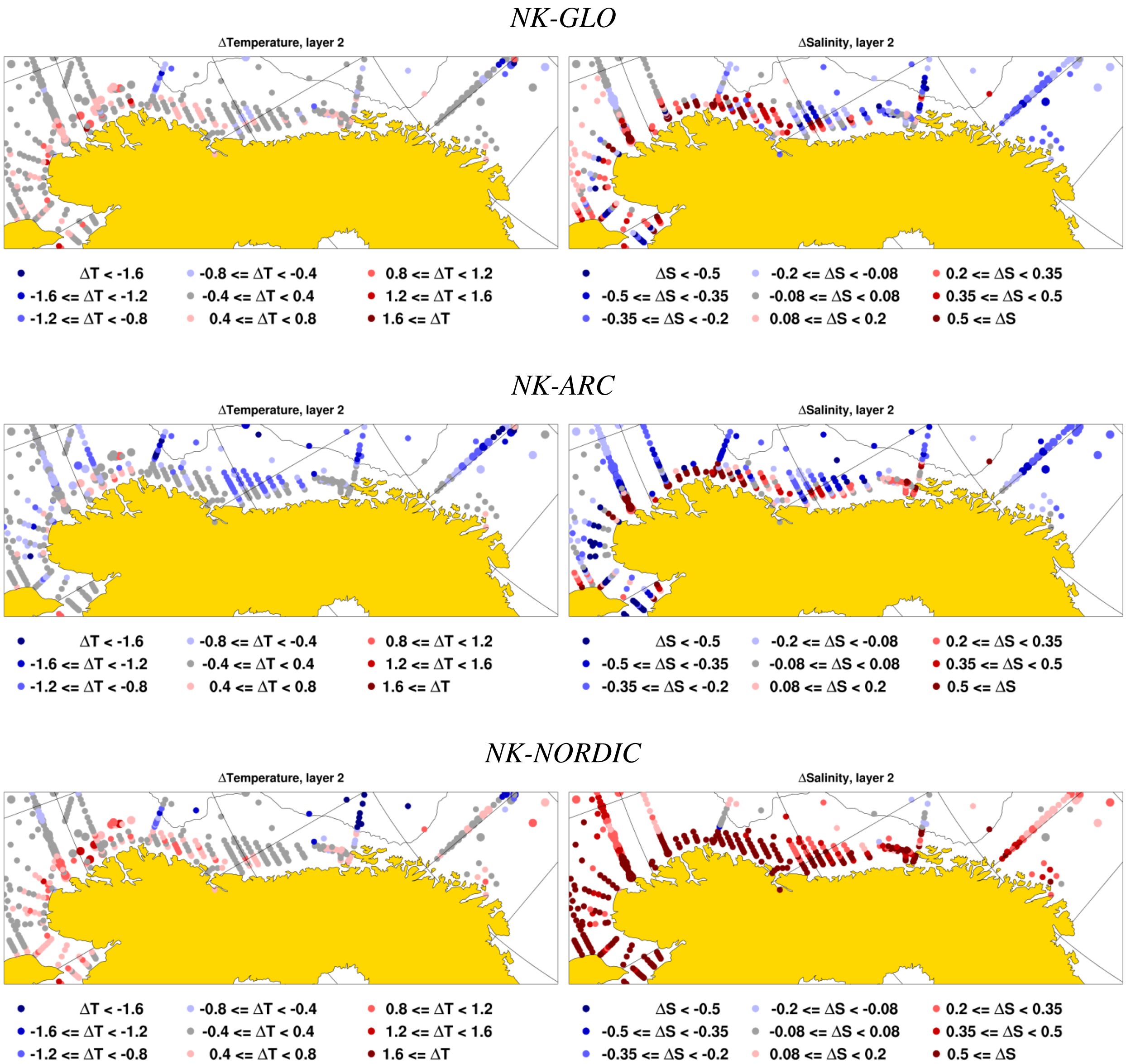

Figure 13: Offset of model results from cruise data for temperature (left) and salinity (right). Model results and observations were averaged over the 10–30 m layer.

4 Recommendations

The OBC experiments were initialized on 2014-07-01. In Section 3.3, we found that the differences in the evolution of results for salinity and temperature had saturated in 2015-01. Hence, our recommendations will be based on results for the final six simulation months. However, we also need to consider if it is likely that seasonal contrasts exist in the months that cannot be analyzed due to this six month limitation.

In the present study we have found that replacing *RN4* with either of the CMEMS

OBC models leads to a large improvement for the representation of salinity in the upper water masses in the *NorKyst-800m* domain.

The choice between the two OBC models from CMEMS is much less clear. The main difference is the quality of the results for temperature, for which a complete picture is lacking since the analysis is restricted as it doesn't span a full year.

We find that during winter, *NK-ARC* has a cold bias (Figure 12). However, the warm bias in *C-GLO* relative to the WOA July climatology in the region of the *NorKyst-800m* boundary (Figure 6) might well spread into the latter domain in the subsequent months. Hence, the unknown quality of the results for temperature in the last half year makes it difficult to conclude that one of the OBC models from CMEMS yields better results in a *NorKyst-800m* configuration than the other.

One shortcoming of the *C-ARC* results that should be ameliorated if this is chosen as the OBC model is the coarse vertical resolution (see the listed depths for "2 *CMEMS-ARC TOPAZ*" in Section 2.2). A large portion of the open boundaries in the *NorKyst-800m* configuration are in shallow waters, and unnecessary vertical interpolation should be eliminated.

Moreover, we also concede that in an operational setting, issues that are of a more technical nature are of considerable importance. Matters such as availability of results from the chosen OBC model as well as reliability of file transfer processes should likely be taken into account when a decision regarding choice of OBC model is made.

Acknowledgements

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Appendix

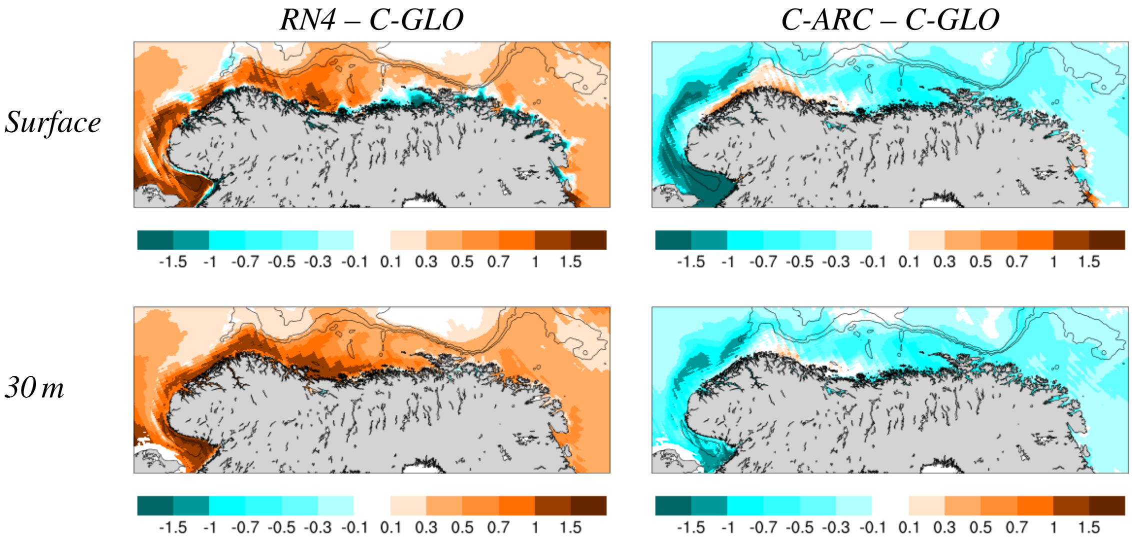

Figure A1: As Figure 4, but differences for 2015-06.

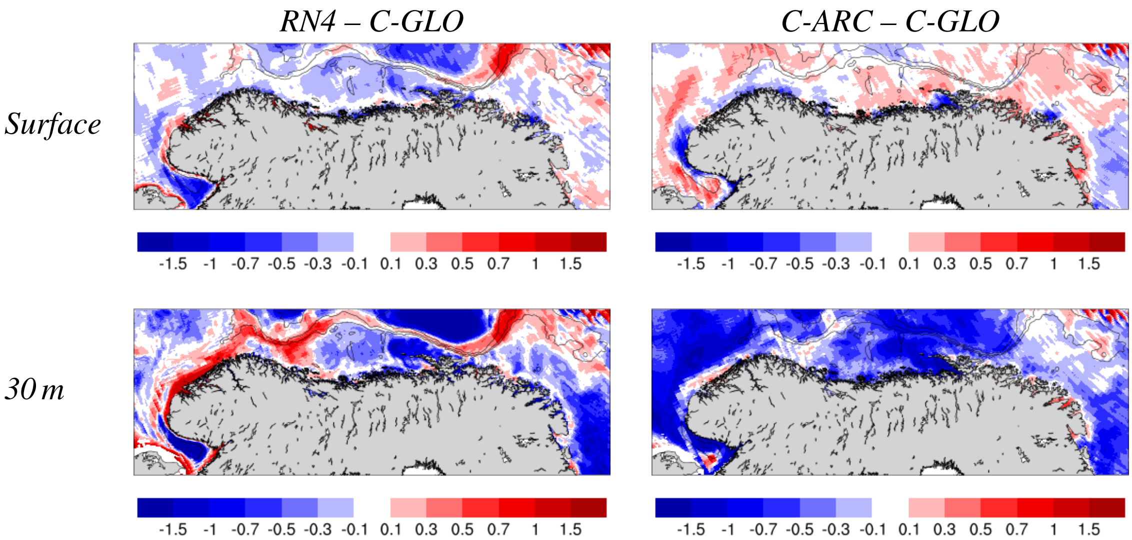

Figure A2: As Figure 5, but differences for 2015-06.

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