Norwegian
Meteorological
Institute

MET report

no. 11/2014
Oceanography

BaSIC Validation - Addendum 2

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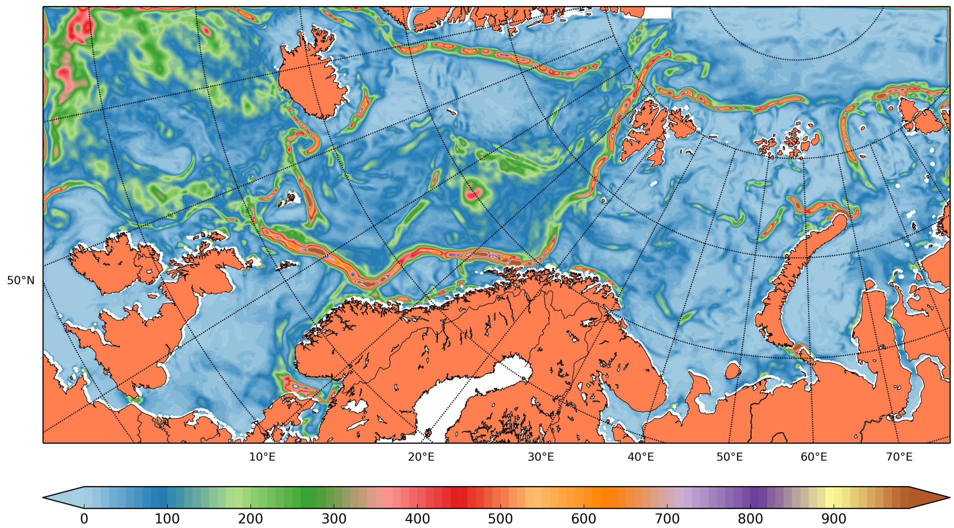

Norwegian Meteorological Institute

MET report

Title	Date
BaSIC Validation - Addendum 2	June 23, 2014
Section	**Report no.**
Ocean and Ice	11/2014
Author(s)	**Classification**
Nils Melsom Kristensen, Arne Melsom, Yvonne Gusdal, Lars Petter Røed, Bjørn Ådlansvik (IMR), Jon Albretsen (IMR)	○ Free ● Restricted
Client(s)	**Client's reference**
Statoil	Contract: 4502465983

Abstract

We consider results from a three-year hindcast for the years 1999-2001 for the Nordic Seas using the ocean model ROMS for the two grid resolutions 4 and 2 km. Furthermore we briefly consider results from a one year (1999) test run in which we compare the results with and without relaxation toward's a preliminary monthly mean SSS climatology. We find that all three hindcasts have problems with polar water held back north of the Denmark Strait, and that this has serious consequences for the hydrography and sea ice extent in the Greenland, Iceland and Norwegian Seas leaving the Barents Sea more or less unaffected. Morever we find that relaxing toward's a monthly mean sea surface salinity is more important than increasing the resolution from a 4 to a 2 km grid.

Keywords

Oceanography, Numerical Modeling, Shallow Water

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1 Introduction

This is addendum no. 2 to the MET report no. 12/2013 (*Røed et al.*, 2013) and is a follow up to Addendum 1 (MET report no. 32/2013, *Kristensen et al.*, 2013). We present

1. an analysis and evaluation of results from a hindcast performed for the two-year period 2000-2001 based on the BaSIC4 model and the new BaSIC2 model,

2. the method used and some preliminary results regarding the generation of a new surface salinity climatology for the Nordic Seas, and

3. an analysis and evaluation of the results from a preliminary test run for the year 1999 in which we relax the surface salinity toward's a first version of the salinity climatology.

The decision to perform these tasks is based on the recommendations made in MET report no. 32/2013 and the recommendations agreed with Statoil in the Pre-production summary meeting December 18, 2013.

2 Comparison of the BaSIC4 and BaSIC2 configurations

The rationale for the comparison is to test whether a 2 km grid resolution provides a significantly better results than a 4 km grid resolution. If not the computer power and capacity is perhaps better spent extending the 4 km grid domain rather than running a smaller domain with a 2 km grid resolution.

To perform an evaluation we ran the two grid resolutions BaSIC2 and BaSIC4 for the three-year period 1999 - 2001. The domain and orientation of the two grids are shown in Figure 1 also displaying the kinetic energy of the barotropic currents (cf. Section 2.1.1). For analysis purposes we saved daily mean values of currents, hydrography and sea ice concentration for the two-year period 2000-2001 only. All runs were initialized using results from the 20 km grid resolution model (BaSIC20). Furthermore we used a grid configuration in which BaSIC4 was nested into BaSIC20 and BaSIC2 into BaSIC4.

2.1 Model results

2.1.1 Kinetic energy

In accord with *Røed and Fossum* (2004) we refer to three types of kinetic energies, namely

- the average kinetic energy, hereafter referred to as the *total kinetic energy* (TKE),

- the kinetic energy associated with the average current, henceforth referred to as the *mean kinetic energy* (MKE), and

- the kinetic energy associated with the eddy motion, henceforth referred to as the *eddy kinetic energy* (EKE).

Note that the averaging is performed over either the two-year period 2000-2001 or the one-year period 1999. Let $\mathbf{u}$ denote the daily mean current. Then if we let $\overline{\mathbf{u}}$ denote the average or mean current, then $\mathbf{u}' = \mathbf{u} - \overline{\mathbf{u}}$ is the eddy motion, that is, the current left when subtracting the mean currents from the daily mean currents. Thus

$$\text{TKE} = \frac{1}{2}\overline{\mathbf{u}^2}, \quad \text{MKE} = \frac{1}{2}\overline{\mathbf{u}}^2, \quad \text{and} \quad \text{EKE} = \frac{1}{2}\overline{\mathbf{u}'^2}, \tag{1}$$

and hence that

$$\text{TKE} = \text{MKE} + \text{EKE}. \tag{2}$$

The TKE, MKE and EKE using *barotropic currents* or vertically averaged currents as input are displayed in Figures 1, 2 and 3. We note that

- BaSIC2 and BaSIC4 display similar kinetic energy levels and patterns with BaSIC4 having somewhat higher values.
- The well known Lofoten Basin Eddy (LBE) and other eddies are present in BaSIC2, but absent in BaSIC4.

Because of the higher resolution employed in BaSIC2 we would expect it to have somewhat higher energy levels, and in particular somewhat higher eddy kinetic energy levels. So the first point is somewhat surprising. The second point is notable since the LBE, located at about 70^{o}N, 4^{o}E, is a well known and documented feature (*Köhl*, 2007; *Koszalka et al.*, 2011; *Søiland and Rossby*, 2013, and references therein). Hence the LBE should be present in any simulation which includes the Lofoten Basin area.

2.2 Evaluation

As in the previous reports (e.g. *Kristensen et al.*, 2013) we evaluate the currents using combined qq-plots and scatter diagrams of speeds and probability distibutions of speeds and directions. Furthermore we evaluate temperature and salinity using probability distributions of differences, spatial distribution of differences and scatterplots. Finally we evaluate sea ice by comparing modeled and observed time series of its total area and extent.

2.2.1 Currents

The basis for the qq- and scatterplots and probability distributions shown in Figures 5 - 9 are observed and modeled daily mean currents at stations CM1-CM5 at 125 m depth and at the bottom. These station are all located along the Fugløya - Bjørnøya Section (Figure 4). We also include qq- and scatterplots of hourly mean currents at stations FB2, FB2B, FB3 and FB4 (Figure 7). The latter positions are collocated with stations CM2, CM3 and CM4.

In line with the energy analysis we note that there are little differences between the two models to indicate that one has an advantage over the other.

2.2.2 Temperature and salinity

We limit the analysis to the upper 100 m water column. The observations are extracted from the World Data Atlas (*Boyer et al.*, 2009). Figures 10 - 14 reveal that the two grid resolutions give quite similar results. Based on these results alone it is impossible to decide whether one grid resolution is better than the other.

We note, however, that both BaSIC2 and BaSIC4 yields water masses that are too cold fresh in the Greenland, Iceland and Norwegian (GIN) Seas. This is probably due to polar water (PW) masses being restrained by too little flow through the Denmark Strait. In turn this leads to an advection of the surplus PW eastward north of Iceland along the Iceland-Faroes-Scotland Ridge (IFSR) causing the differences in the GIN Seas (cf. Figures 11 and 12).

As expected, and reported earlier (*Røed et al.*, 2013; *Kristensen et al.*, 2013), we note that the Norwegian coastal water is too salty. Moreover, we note that the polar water in the Barents Sea east and south of the Svalbard Archipelago is too salty as well.

2.2.3 Sea ice area and extent

Figure 15 shows the time evolution of modeled and observed sea ice area and extent for the two-year period 2000 - 2001. The observations are extracted from the OSI SAF archive (*Eastwood et al.*, 2011). Again there is small differences between the two grid resolutions, except that BaSIC2 gives a smaller winter maximum. Again using biases and standard deviations as measures there is no indication that one has an advantage over the other.

2.3 Discussion

In summary we find that

- BaSIC2 and BaSIC4 displays similar kinetic energy patterns, with BaSIC4 having somewhat higher energy levels.
- LBE is present in BaSIC2, but is missing in BaSIC4,
- both appear to restrain the flow of polar water (PW) through the Denmark Strait between Iceland and Greenland with serious implications for the GIN Seas, and finally
- a comparsion of modeled and observed currents, hydrography and sea ice do not justify the use of a higher grid resolution model.

The first bullet point is somewhat surprising. We expected BaSIC2 to show higher energy levels, in particular eddy kinetic energy levels, because of its higher resolution. The second bullet point is, however, more in line with our expactions. Because of the higher resolution BaSIC2 is more prone to instabilities, and hence generates eddies more readily than BaSIC4. This is indeed necessary to maintain the semi-permanent LBE (cf. Section 4.3).

Regarding the third bullet point we note that most of the difference between observations and model results are in the GIN Seas, which generally is too fresh and too cold in both BaSIC2 and BaSIC4. We hypothesize that this is caused by the flow of polar water (PW) through the Denmark Strait being restrained Hence the PW tends to pile up north of the strait and to be advected eastward along the norhtern coast of Iceland and continuing along the Iceland-Faroes-Scotland Ridge (IFSR) where it mixes with water of Atlantic origin flowing into the Nordic Seas across the IFSR. Thus the upper water masses also in the Norwegian Sea tends to be colder and fresh on average too. As shown below (Section 4) this also impacts the sea ice cover and extent.

As noted in the fourth bullet point the model minus observation differences are about the same in the two models. Thus the higher resolution in BaSIC2 appears to have no impact on the results in the GIN Seas compared to BaSIC4. Hence these results gives no indication that one of the grid resolutions has an advantage over the other. We remark though that the problem of too cold and too fresh waters in the GIN Seas needs to be solved before embarking on a long term production. Finally we note that that the comparison of currents, although limited to the Fugløya - Bjørnøya section in the Barents Sea Opening only, does not indicate that one of the grids have an advantage over the other. We dicuss these points further in Section 5.

3 A new monthly climatology for sea surface salinity

A new monthly sea surface salinity (SSS) climatology is presently being generated. In particular a new climatology for the coastal water is needed. The idea was that the new climatology should use EKASC data (*Engedahl et al.*, 1998) as input and adding all the coastal CTD data residing in the Institute of Marine Research (IMR) databases to replace the EKASC data close to the coast. Based on this idea a first version of a new climatology was made of which Figure 16 provides an example. This work is still ongoing, and we emphasize that the generation of a monthly SSS climatology is not straightforward and several methods are presently investigated.

At the meeting April 3 the preliminary results was discussed and it was decided to replace the EKASC SSS climatology with a climatology based on the FOAM reanalysis data. The rationale is that this is more consistent with the fact that we will use the FOAM reanalysis as lateral boundary conditions for the BaSIC20 (or outer model grid). Hence the new SSS climatology will be consistent with the lateral boundary conditions. Moreover, to be able to perform a hindcast starting 1985 we have to make a climatology based on the FOAM reanalysis for lateral input to BaSIC20 for the years prior to 1993 anyway.

4 Impact of salinity relaxation

To test the impact of a new monthly mean SSS climatology we have run the BaSIC4 grid configuration with and without relaxation toward's a preliminary mean monthly SSS climatology for the one year 1999. The preliminary climatology is an early version of the one now being generated. We emphasize that the rationale is to investigate the impact of relaxing toward's a monthly mean SSS climatology rather than expecting more realistic results at this stage in the process. Nevertheless we have performed an evaluation against observed hydrography and sea ice.

4.1 Model results

4.1.1 Kinetic energy

Figures 17 - 19 show respectively the TKE, MKE and EKE using the barotropic currents as input. The figures compares the results using BaSIC4 with and without relaxation.

We note that despite the average period is now one year only, and that 1999 is kind of a spin-up year, the kinetic energy level is comparable to the levels from the two-year average depicted in Figures 1 - 3. We also note that the energy level in all energy compartments is increased significantly when relaxing toward's the SSS climatology. Particulary notable is that when relaxing toward the SSS climatology the LBE crops up also in BaSIC4. Thus it appears that it is more important to relax toward's an SSS climatology than to employ a higher resolution model.

4.1.2 Sea ice

Figure 20 shows the distribution of the highest sea ice concentration (SIC) experienced throughout the year 1999 with and without relaxation. Note the pile up of ice north of the Denmark Strait and north of Iceland, which becomes more severe when we turn on the relaxation. We also note that the maximum distribution in the Barents Sea is more or less insensitive to the relaxation.

4.2 Evaluation

4.2.1 Hydrography and sea ice

Figures 21 - 24 show the impact of relaxing toward's an SSS climatology on hydrography and sea ice. Depicted are the probability distribution differences, the spatial anomaly of the temperature and salinity, scatter plots of temperature and salinity and finally the sea ice extent. All figures are based on results using BaSIC4 for the one-year 1999.

4.3 Discussion

In summary we find that

- relaxing toward's a monthly mean SSS climatology has a major impact on the results,
- BaSIC4 with SSS relaxation has a kinetic energy level that is comparable or slightly higher than BaSIC2 without relaxation,

- the Lofoten Basin Eddy crops up in BaSIC4 when turning on the SSS relaxation,
- the relaxation appears to have no impact on the flow of polar water through the Denmark Strait,
- the Barents Sea ice and hydrography are mostly unaffected.

The second bullet point is somewhat surprising and unexpected. A possible explanation is that the relaxation toward's the monthly mean SSS climatology gives stronger density fronts due to increased salinity gradients, in particular along the Norwegian coast. In turn the strenghtening of the fronts leads to stronger currents that makes them more prone to instabilities.

As noted in the third bullet point the Lofoten Basin Eddy (LBE) crops up in the BaSIC4 grid when relaxing. Since the LBE is a semi-permanent nature, its survival in the BaSIC4 grid strongly supports the above hypothesis. Without being continuously fed by eddies propagating westward from their birthplace along the Norwegian coast, the LBE would otherwise vanish.

As noted in Section 2.3 the fourth bullet point highlights a problem that must be solved before starting the production. A possible hypothesis is that the piling up of polar water is due to the location of the open boundary being too close to the Denmark Strait. Hence the problem may be solved by moving the open boundary of the BaSIC4 grid further south, an option that is attractive also for other reasons (cf. Section 5).

5 Conclusions and recommendations

5.1 Conclusions

We find that the differences between the BaSIC4 and BaSIC2 grid configurations do not justify the use of the high resolution BaSIC2 grid configuration. The main difference we find is in the kinetic energy levels. Due to its higher resolution the BaSIC2 grid configuration is able to reproduce the well known Lofoten Basin Eddy (e.g., *Koszalka et al.*, 2011; *Søiland and Rossby*, 2013), but so is the BaSIC4 grid configuration when we apply the relaxation toward's the preliminary monthly mean sea surface salinity (SSS) climatology. We therefore conclude that performing a relaxation essentially has the same effect as increasing the grid resolution, and that we may as well use the BaSIC4 grid with relaxation toward's an SSS climatology for the production runs.

The generation of the monthly mean SSS climatology is not without problems. To be consistent with the BaSIC20 grid configuration it should be based on the FOAM reanalysis rather than the old EKASC climatology (*Engedahl et al.*, 1998).

Finally we note that all the results presented show that too much polar water (PW) piles up north of the Denmark Strait. As a consequence the PW is advected eastward along the northern coast of Iceland and further along the Iceland-Faroes-Scotland Ridge (IFSR). Due to this advection the water masses in the Greenland, Iceland and Norwegian Seas becomes too cold and too fresh. As a result too much sea ice forms in the area north of Iceland. However, it does not appear to significantly affect the Barents Sea.

We therefore emphasize that this problem needs to be solved before embarking on the production of a 25 year long hindcast. A possible solution is to extend the BaSIC4 grid so as to avoid having the nesting boundary too close to the Denmark Strait. The latter is made attractative in light of the recommendations below in which we recommend to use the BaSIC4 grid nested into the BaSIC20 grid in the continuation of the BaSIC project.

5.2 Recommendations

Based on the results and discussions above (cf. Sections 2.3 and 4.3) we recommend to:

1. to discard the higher resolution BaSIC2 and make use of a doubly nested grid configuration in which BaSIC4 is nested into BaSIC20.
2. make use of the FOAM reanalysis data on the lateral boundaries of the BaSIC20 domain,
3. make use of a relaxation toward's a monthly mean sea surface (SSS) climatology both for BaSIC20 and BaSIC4,
4. replace the monthly mean SSS climatology based on EKASC by one based on the FOAM reanalysis data
5. extend the BaSIC4 grid to avoid having the nesting boundary too close to the Denmark Strait, and finally
6. perform some test experiments to ensure that the extended BaSIC4 grid solves the problem of too much polar water piling up north of the Denmark Strait, including an investigation of the condition used at the nesting boundary, e.g., play around with how fast we relax toward's the BaSIC20 solution at the nesting boundary.

Acknowledgment

This work is funded by Statoil through Contract No. 4502465983.

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Figures

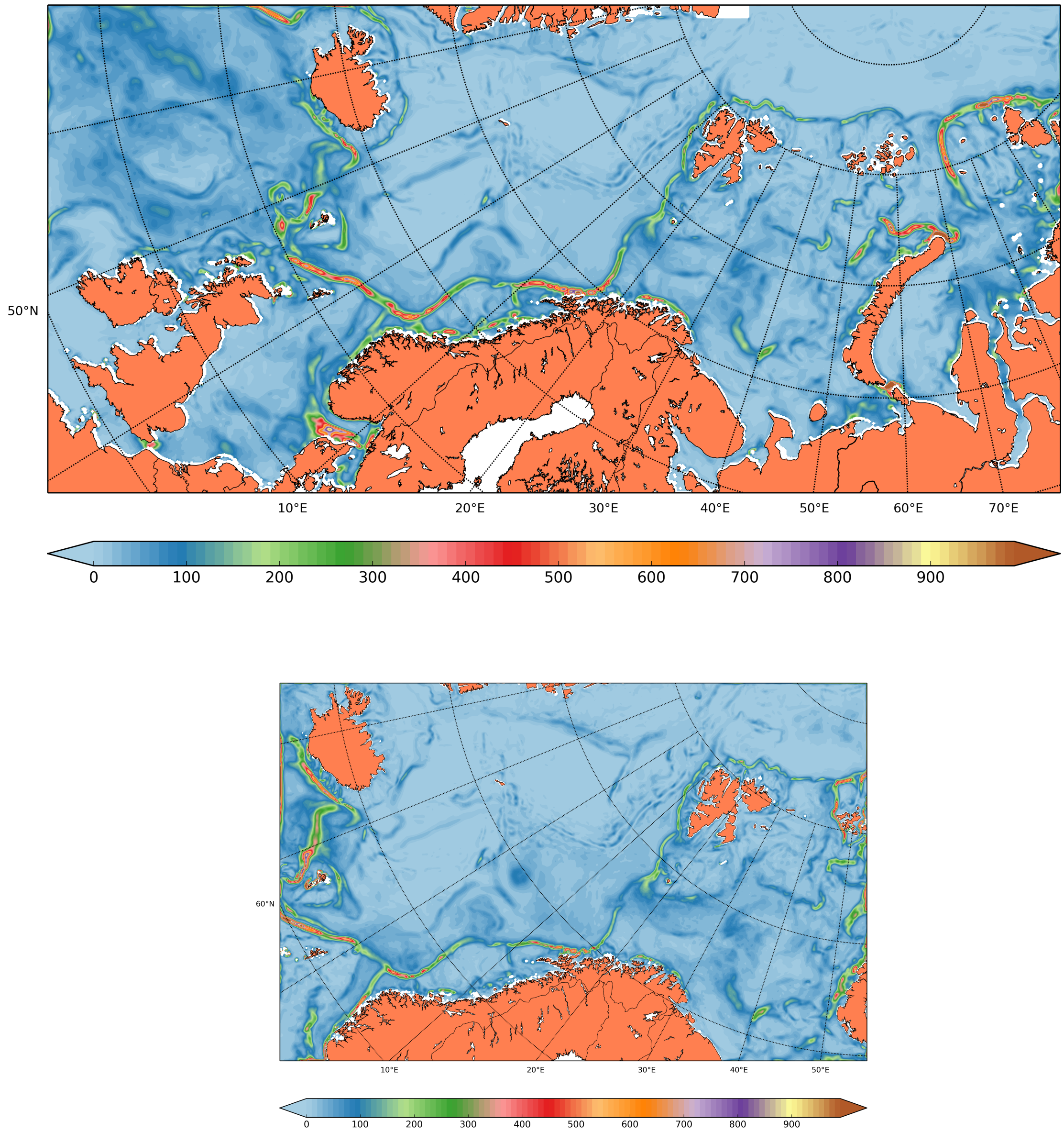

Figure 1: The total kinetic energy (TKE) averaged over the two-year period 2000-2001 associated with the *barotropic* currents (vertically averaged currents). The color bar denotes the energy in cm^2s^{-1}. For an explanation of TKE see text on page 1.

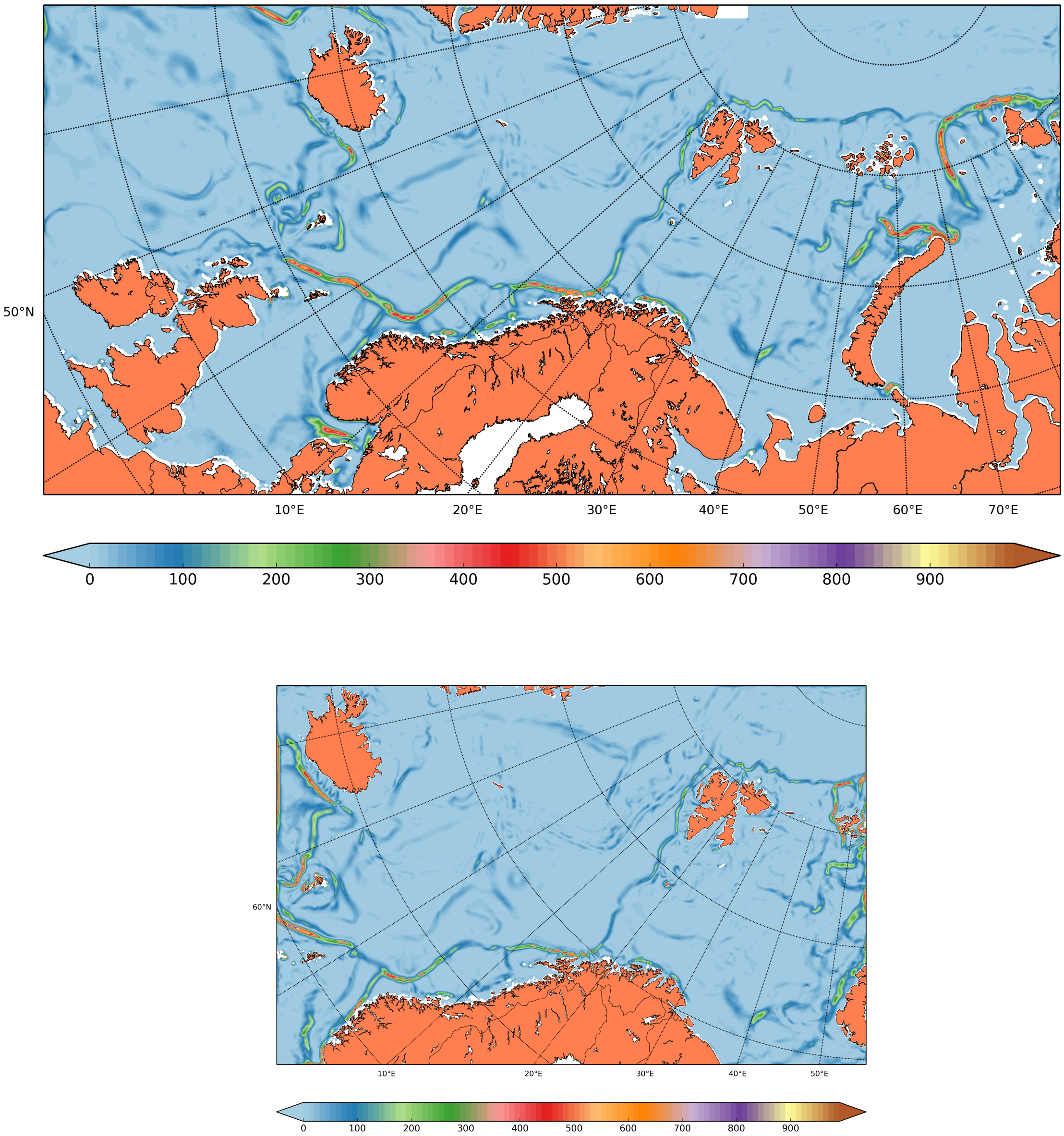

Figure 2: As Figure 1, but showing the mean kinetic energy (MKE). For an explanation of MKE see text on page 1.

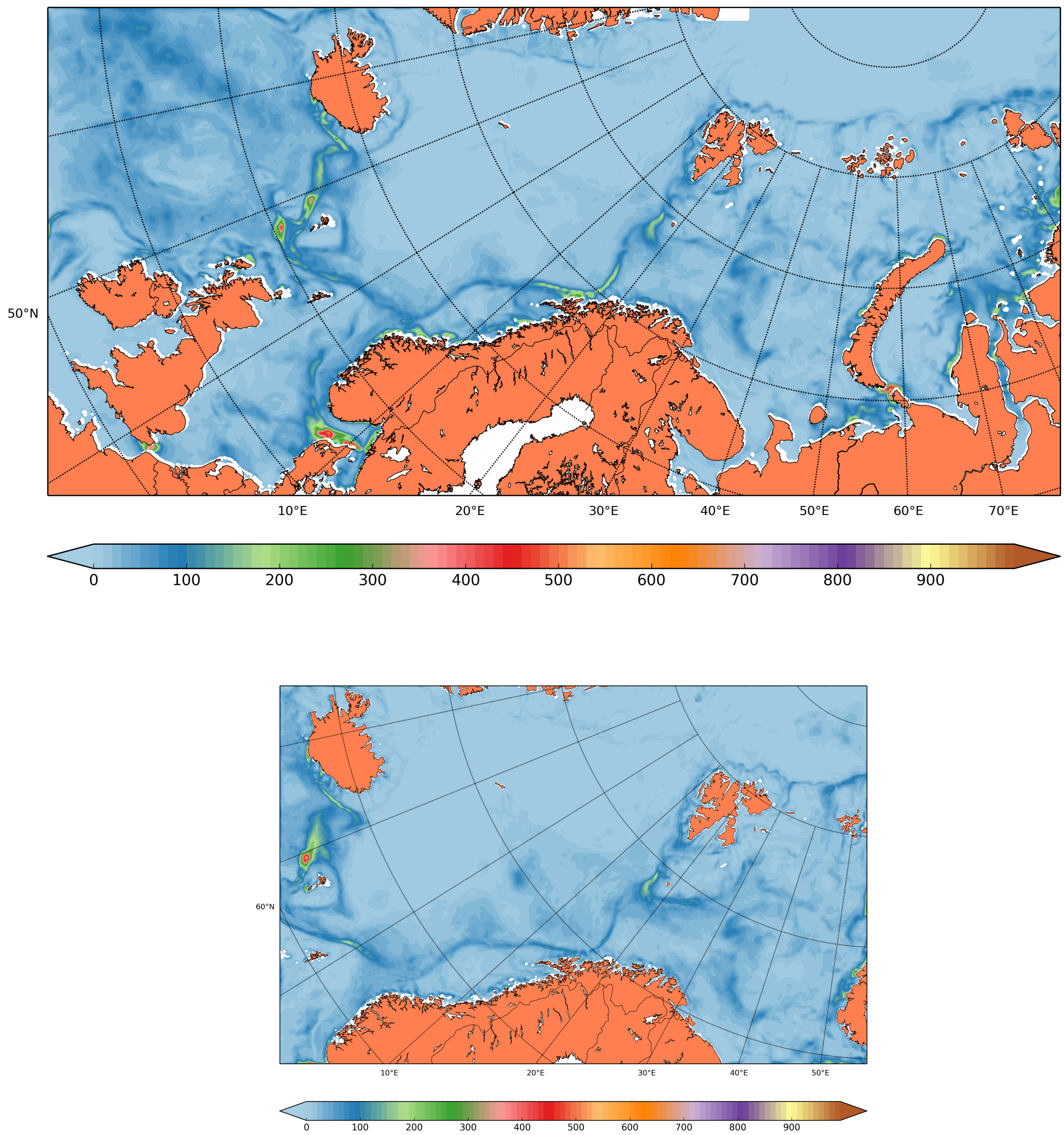

Figure 3: As Figure 1, but showing the eddy kinetic energy (EKE). For an explanation of EKE see text on page 1.

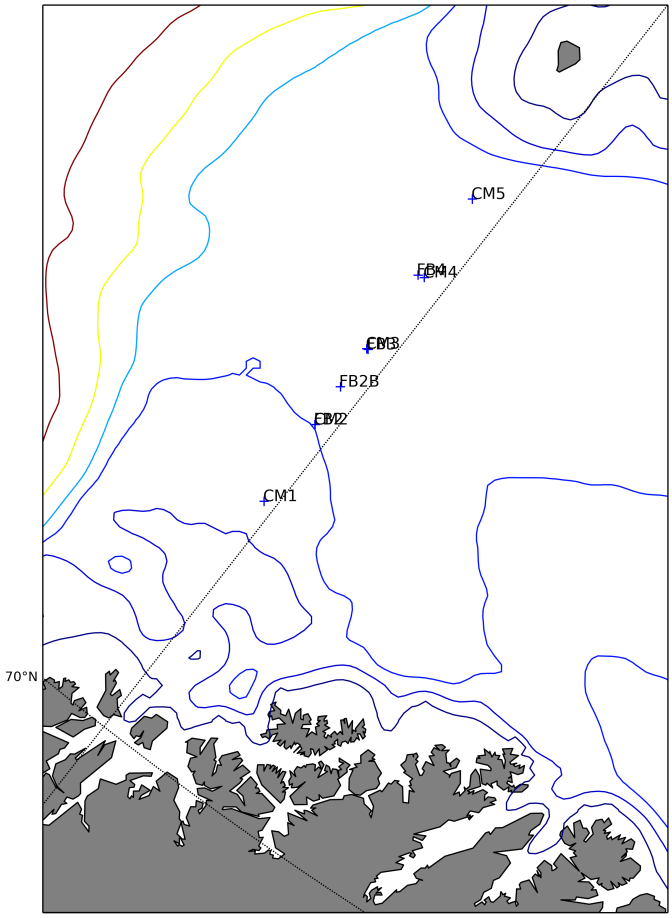

Figure 4: Position of stations for current measurements.

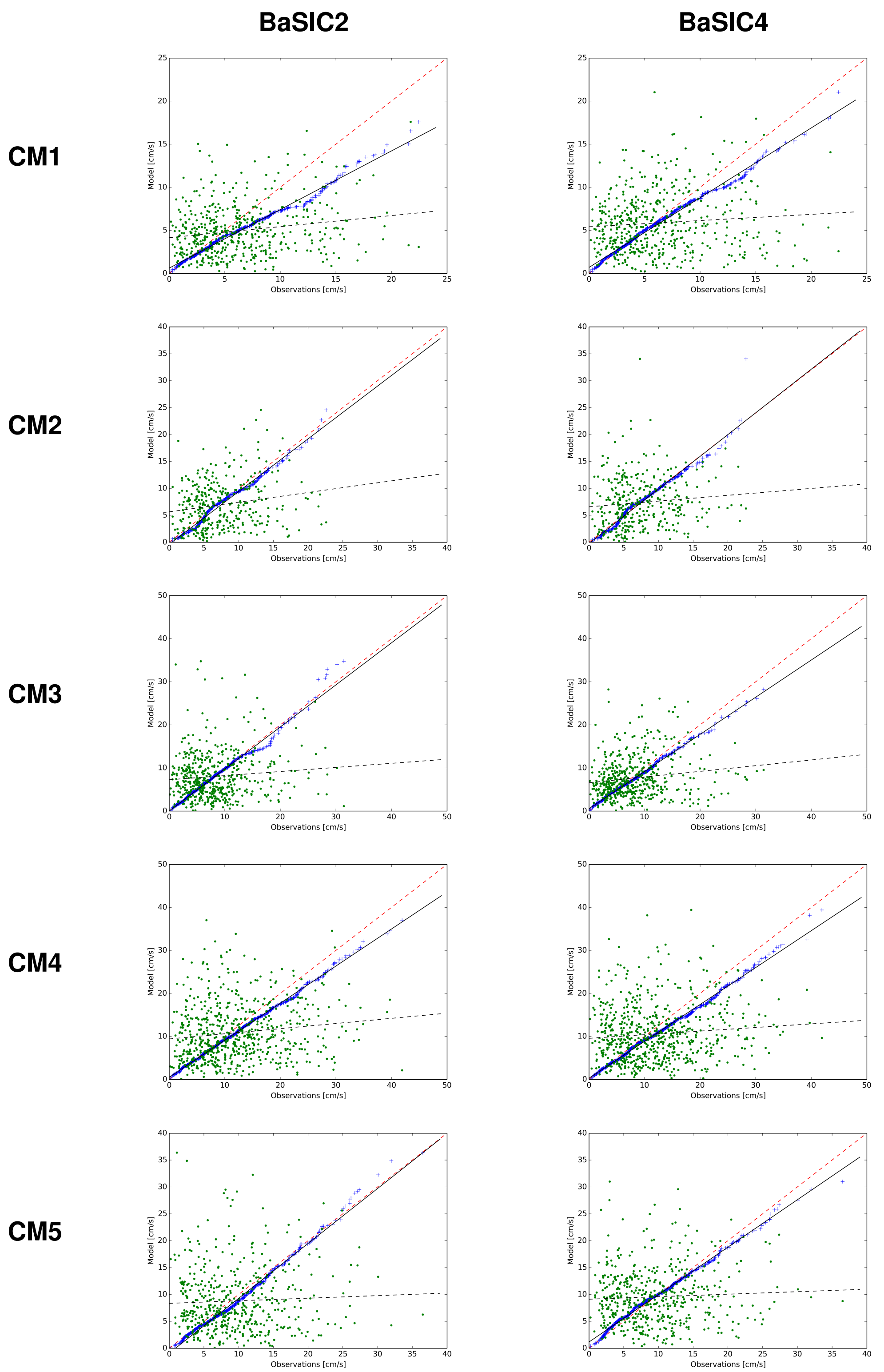

Figure 5: Combined qq- and scatterplots for daily mean current speed at 125 m depth for the years 2000 - 2001. Results are from stations CM1 - CM5 (Figure 4). Left- and right-hand columns are speeds based on the BaSIC2 and BaSIC4 grids, respectively. Observed speeds are along the horizontal axis and modeled speeds along the vertical axis. Green dots belong to the scatterplot, and blue + signs to the qq-plot. Note that the speed scale is 0-25 cm/s for CM1, 0-40 cm/s for CM2 and CM5, and 0-50 cm/s for CM3 and CM4. The red-dashed line is the 1:1 line. The black solid and dashed lines are the linear fit to the qq-points and scatter points, respectively.

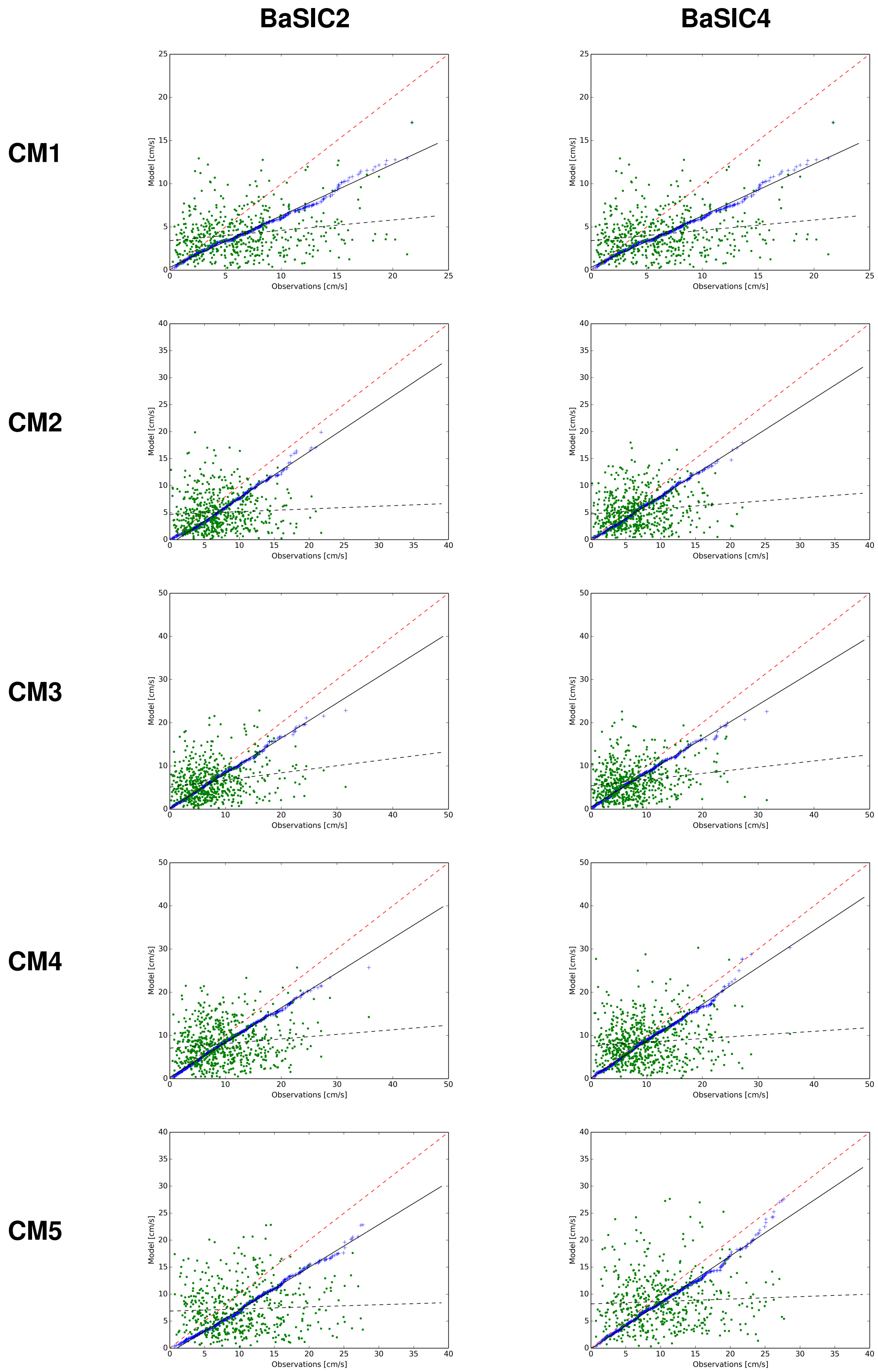

Figure 6: As Figure 5, but for the bottommost current meter.

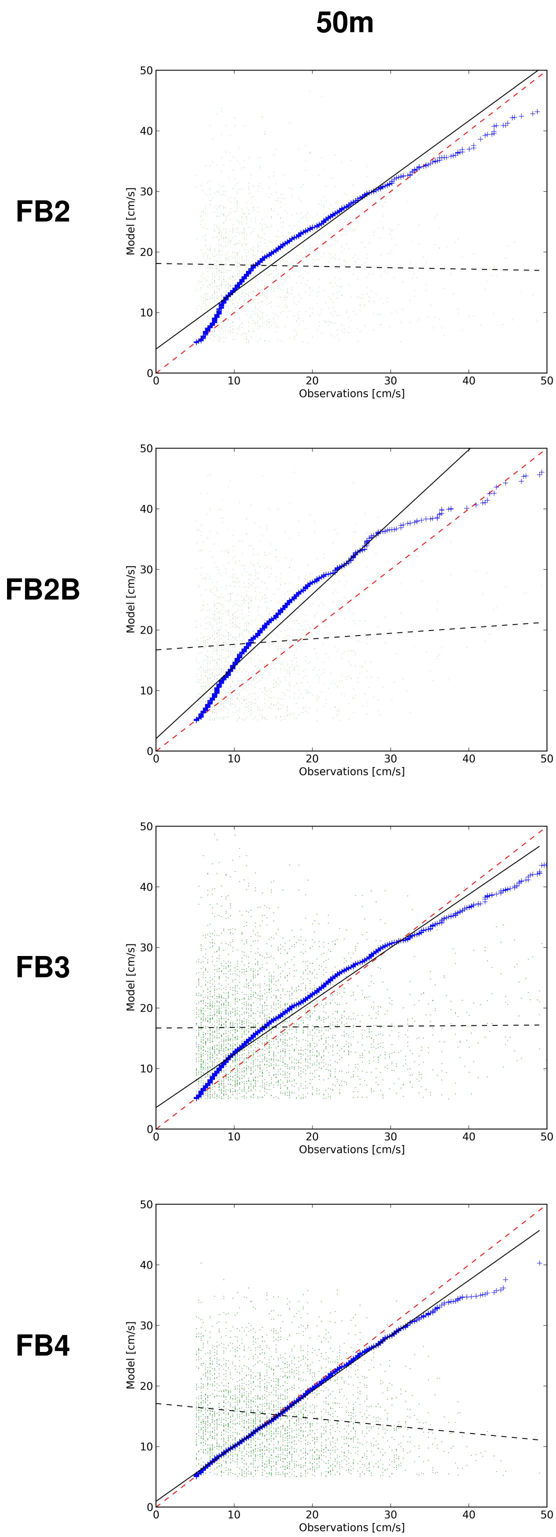

Figure 7: As Figure 5, but using hourly BaSIC2 results and observations at 50 m depth as input. The measurements are from the positions FB2, FB2B, FB3 and FB4, which are collocated with CM2-CM4 (cf. Figure 4).

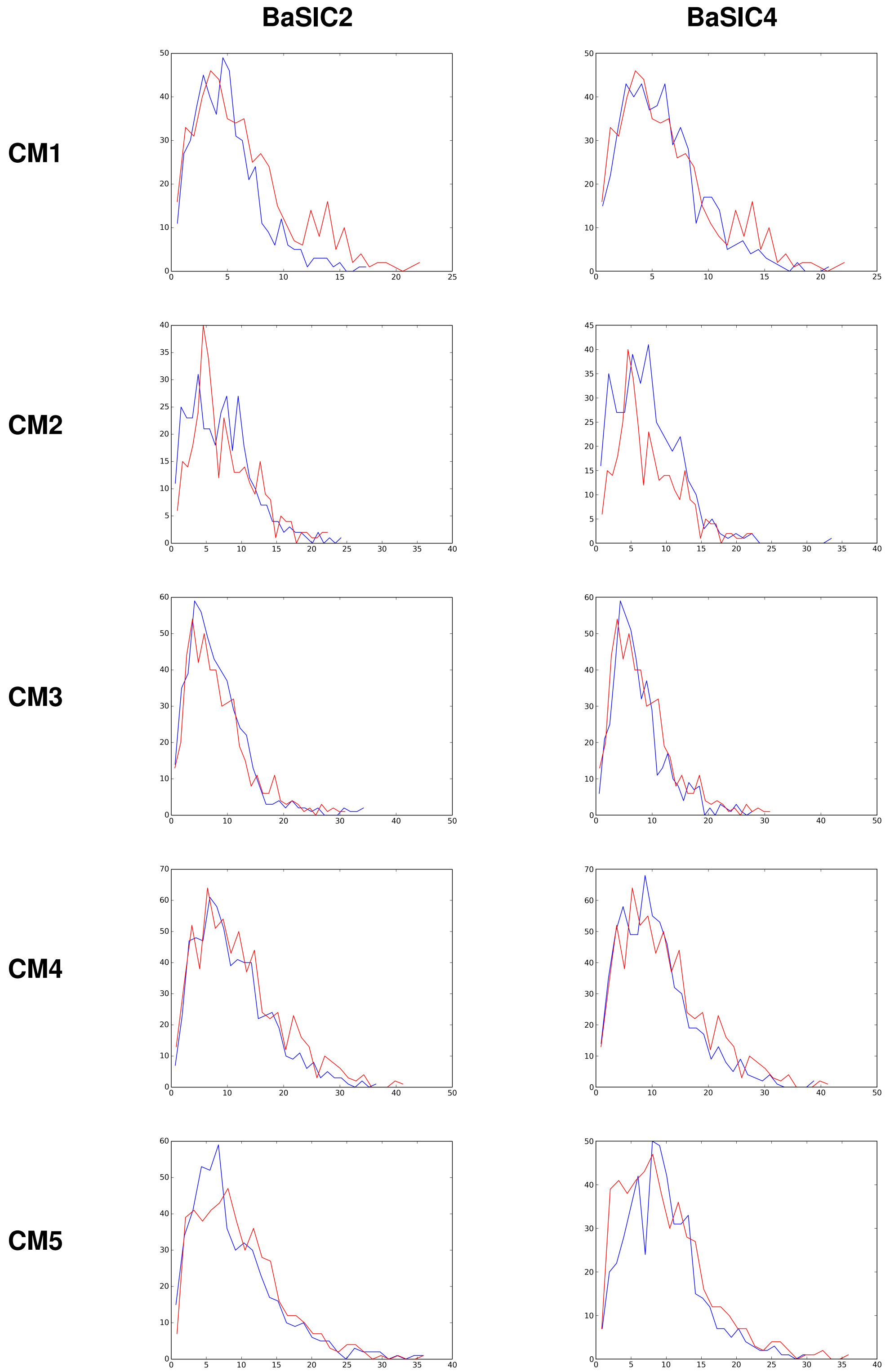

Figure 8: Comparison of observed (red line) and modeled (blue line) probability distributions of current speed at 125 m depth for the years 2000 - 2001. Results are from stations CM1 - CM5 (Figure 4). Left- and right-hand columns are speeds based on the BaSIC2 and BaSIC4 grid, respectively. Speeds along the horizontal axis is in cm/s.

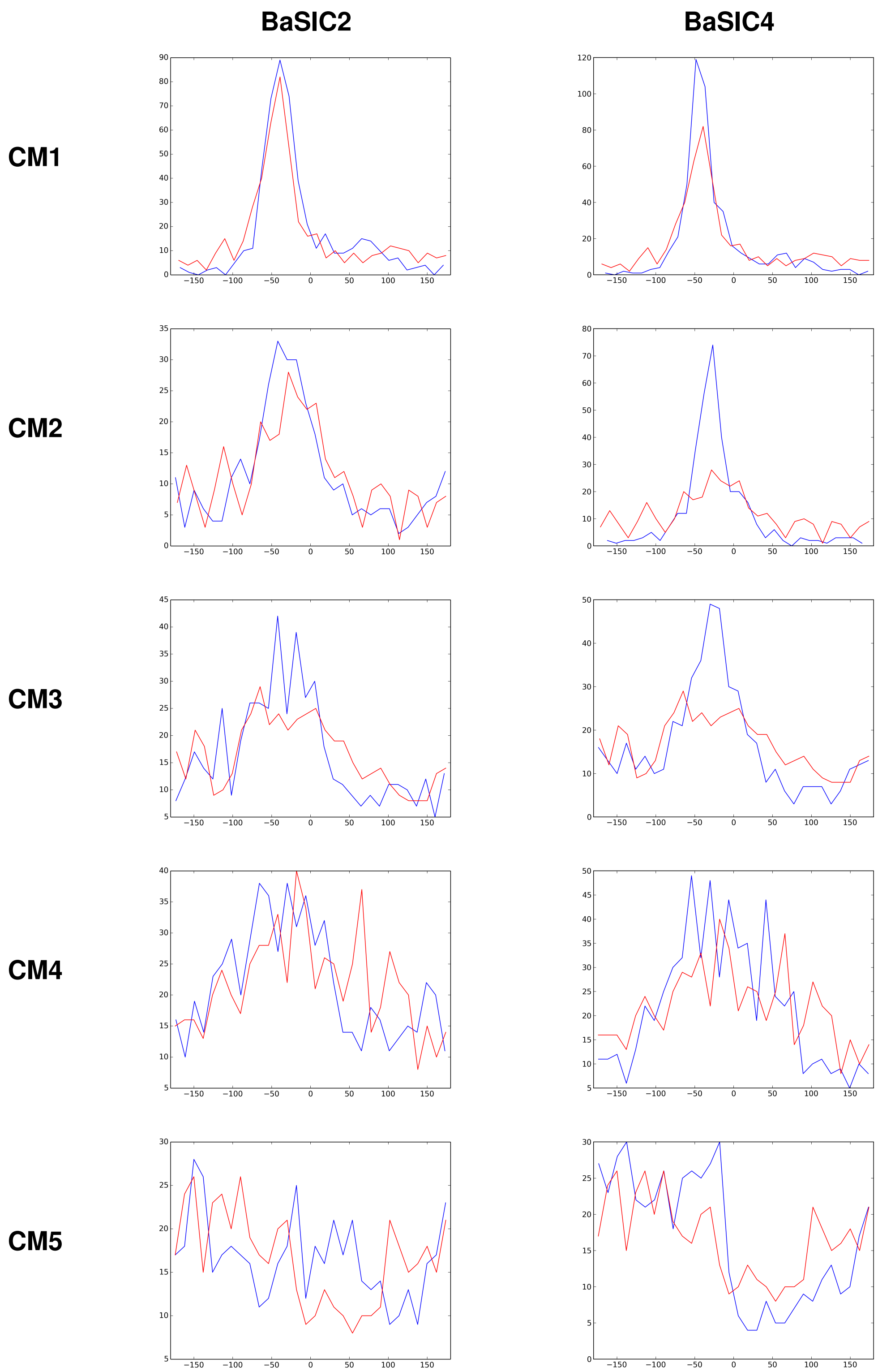

Figure 9: Comparison of observed (red line) and modeled (blue line) probability distributions of current direction at 125 m depth for the years 2000 - 2001. Results are from stations CM1 - CM5 (Figure 4). Left- and right-hand columns are current directions based on the BaSIC2 and BaSIC4 grid, respectively. Direction along the horizontal axis is in degrees N.

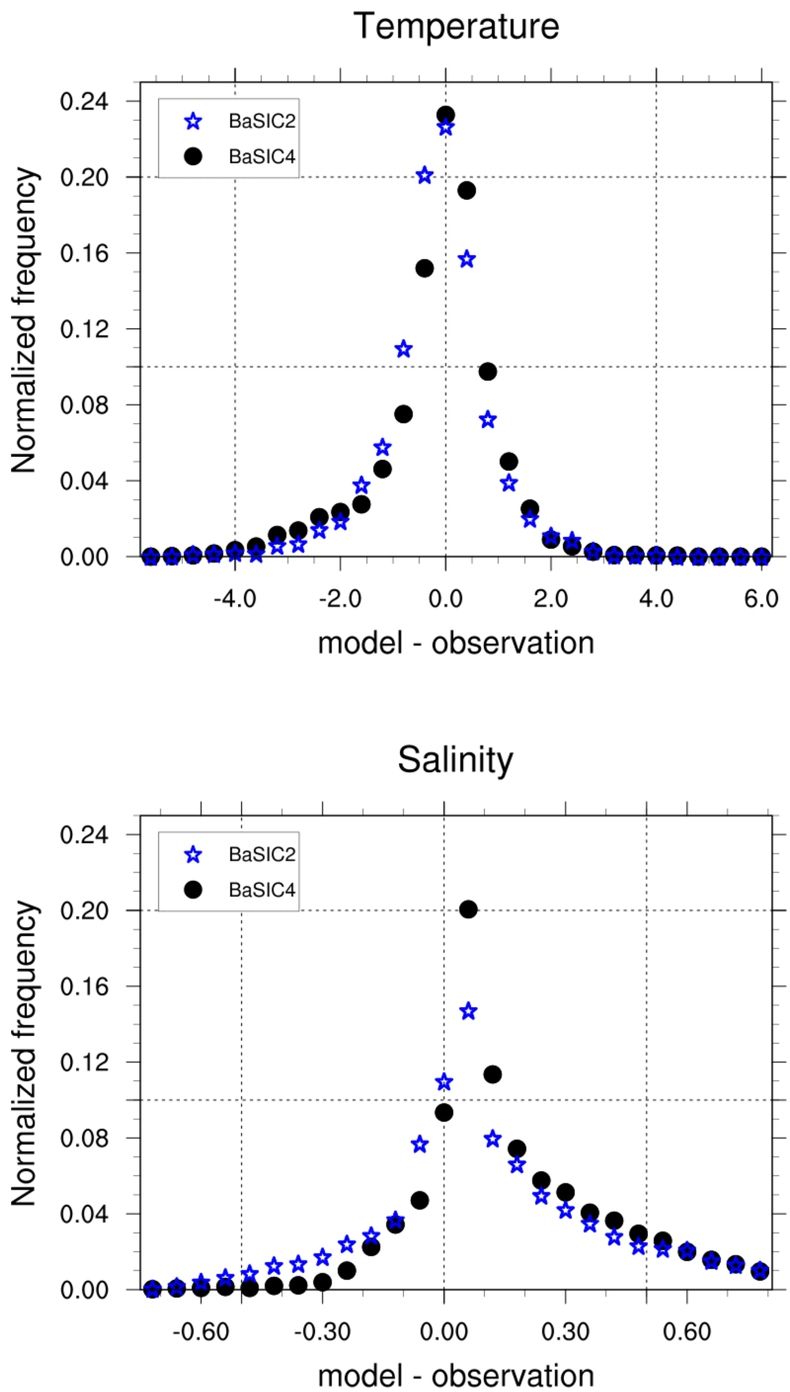

Figure 10: Probability distribution of model results minus observations for the top 100 m temperatures (upper panel) and salinities (bottom panel) for the two-year period 2000-2001. Black filled circles refer to BaSIC4 results while the blue stars refer to BaSIC2 results. The biases regarding temperatures are -0.18 for BaSIC2 and -0.13 for BaSIC4, and regarding salinities 0.24 for BaSIC2 and 0.16 for BaSIC4. Standard deviations regarding temperature are respectively 0.99 for BaSIC2 and 1.07 for BaSIC4, while they are 0.54 and 1.20, respectively, regarding salinity.

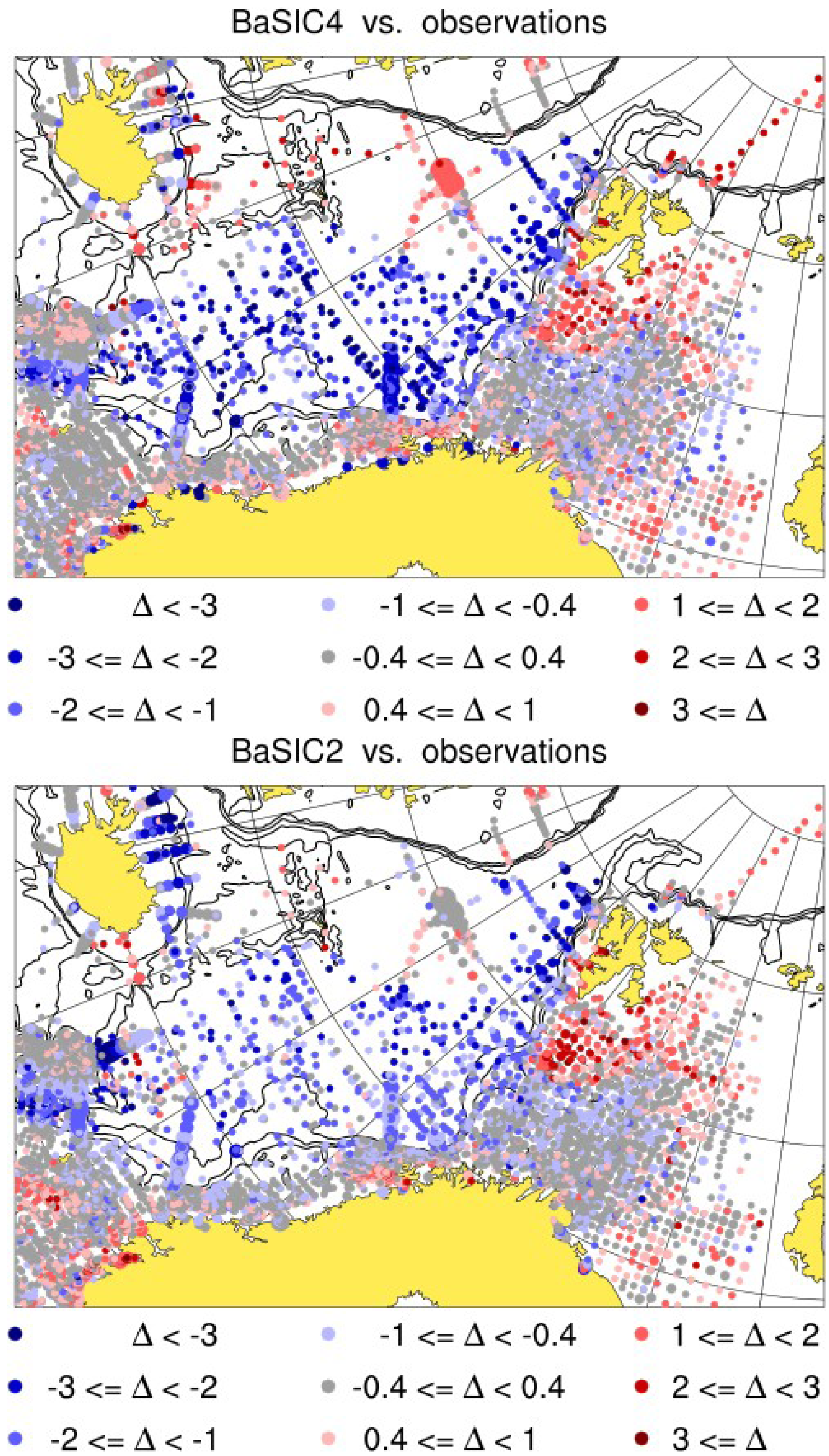

Figure 11: Maps displaying the spatial distribution of temperature anomalies (model minus observations). The relation between the anomalies and each color code is given below the figures. Results from BaSIC4 is shown in the top panel, while results from BaSIC2 is shown in the bottom panel.

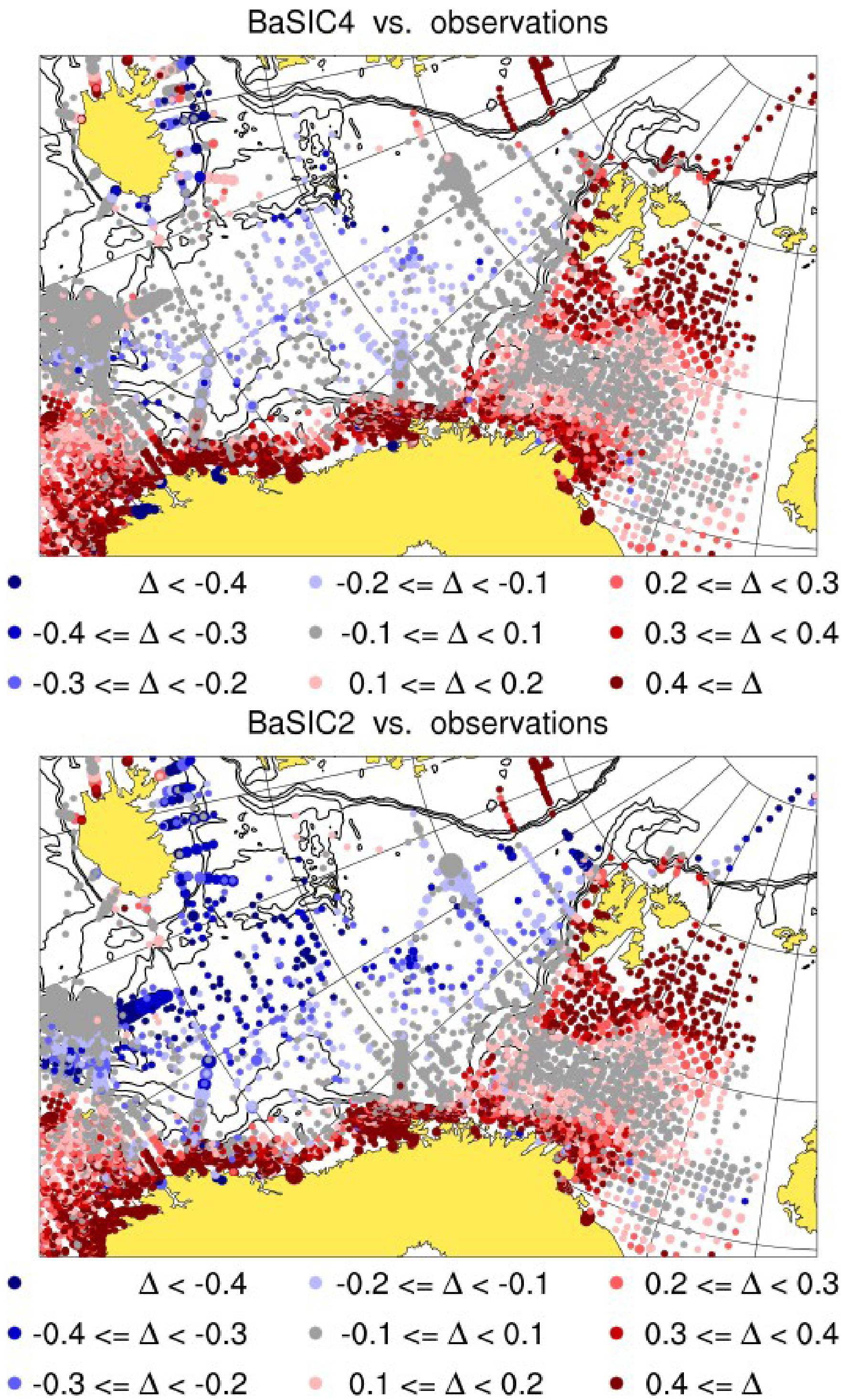

Figure 12: As Figure 11, but showing salinity. Note that both models are too fresh in the GIN Seas, but BaSIC2 more so than BaSIC4.

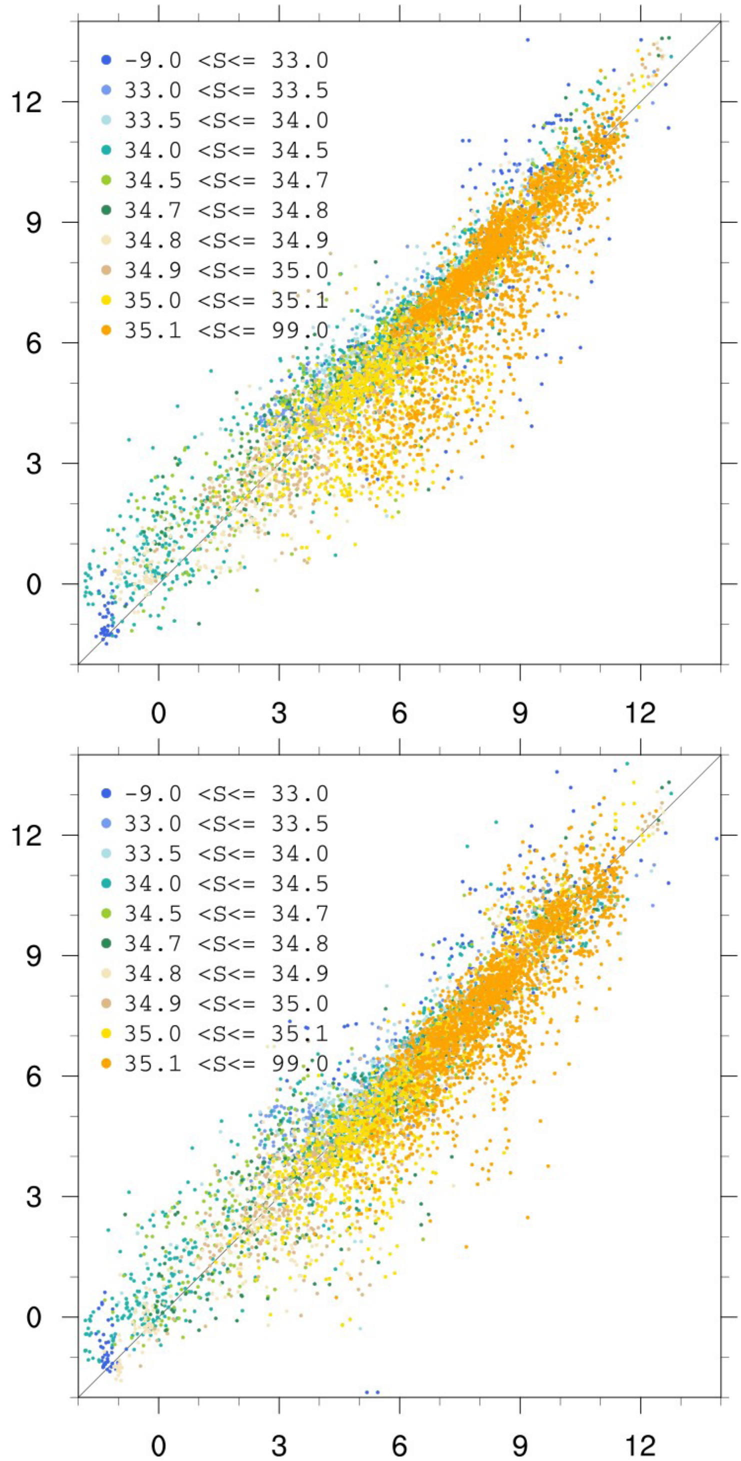

Figure 13: Scatter plots for averaged potential temperature (in ^{o}C) from the upper 100 m of the water column. Top panel shows results from BaSIC4, while the bottom panel shows the results from BaSIC2. Observed temperatures are along the horizontal axis while model results are along the vertical axis. The color code corresponds to the associated salinity average in the observations. High salinity dots are plotted on top of dots with lower salinity.

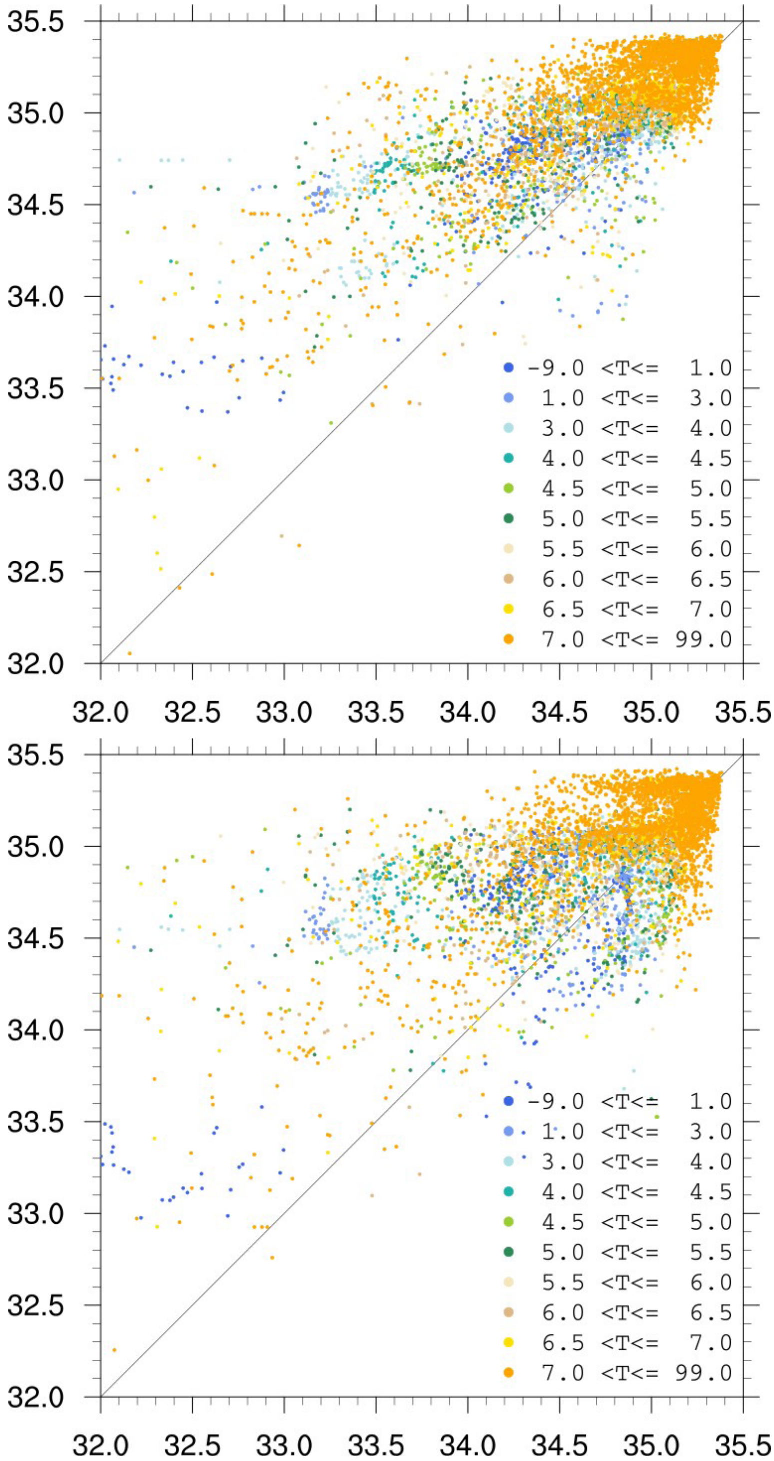

Figure 14: As Figure 13, but for salinity (in psu). The color code corresponds to the associated temperature average in the observations. High temperature dots are plotted on top of dots with lower temperatures.

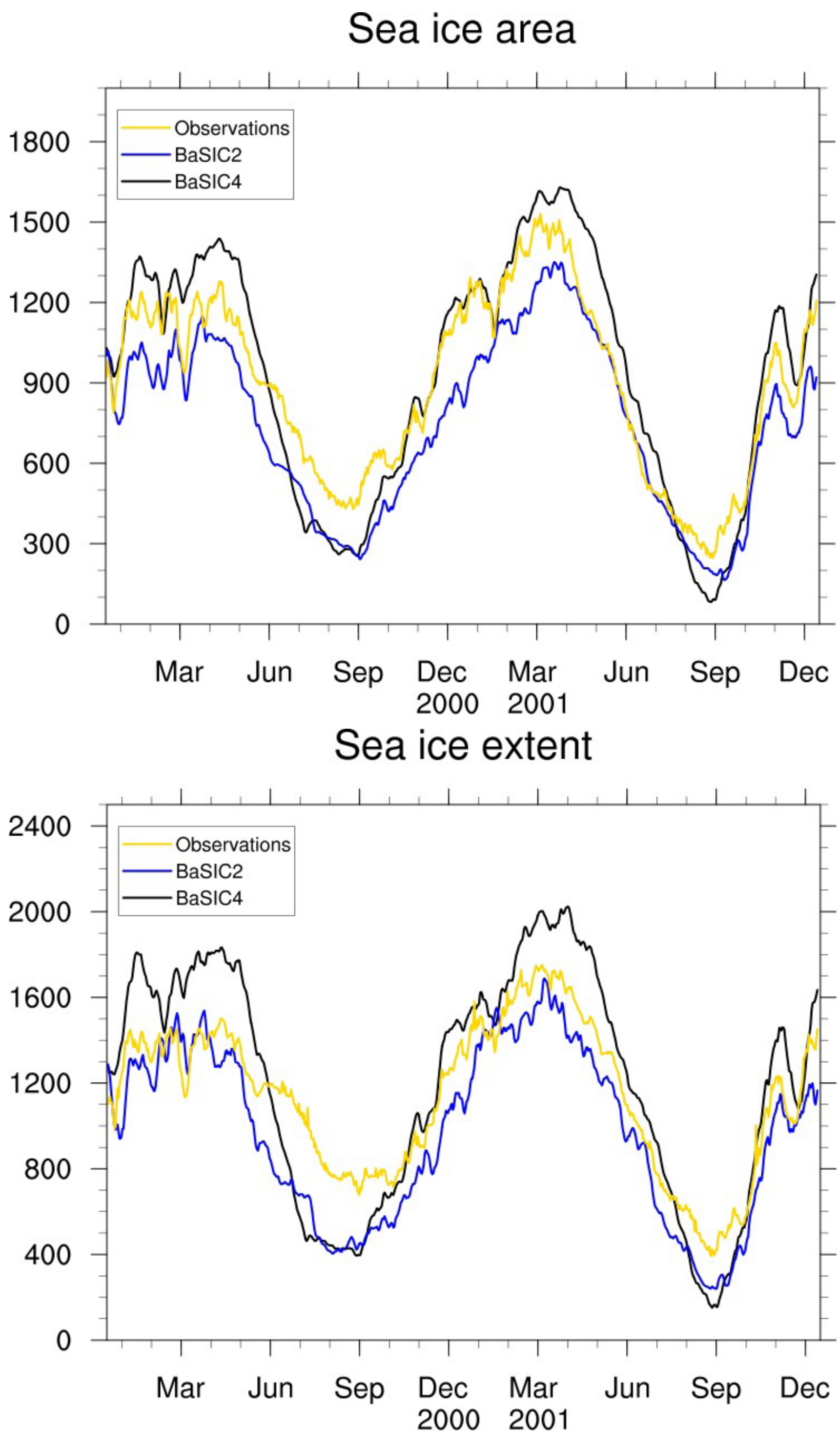

Figure 15: Time series of sea ice area (top panel) and extent (bottom panel) limited to the BaSIC2 domain. Observations are displayed by the yellow line, model results from the BaSIC2 configuration in blue and model results from the BaSIC4 configuration in black. Overall averages (in 1000 km^2) regarding area are 890 (Obs), 750 (BaSIC2) and 930 (BaSIC4), while the similar numbers for sea ice extent are 1130, 970 and 1200, respectively.

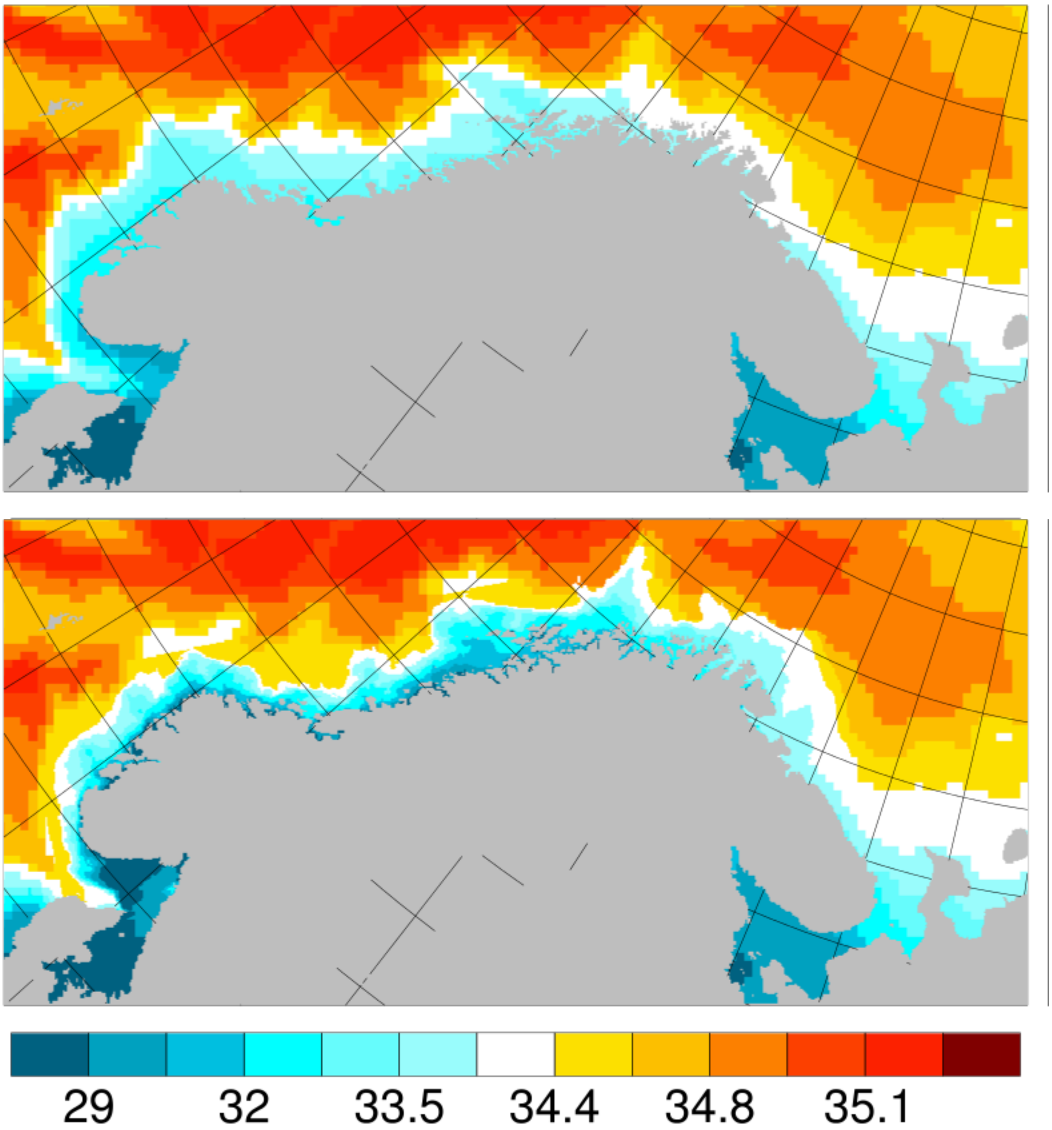

Figure 16: Monthly mean sea surface salinity (SSS) climatology for February based on the EKASC data (*Engedahl et al.*, 1998) and recent Institute of Marine Research (IMR) CTD data sets. Upper panel shows the monthly mean SSS climatology based on EKASC data only, while lower panel shows a preliminary version of a new monthly mean SSS climatology in which the EKASC data have been merged with IMR data along the Norwegian coast.

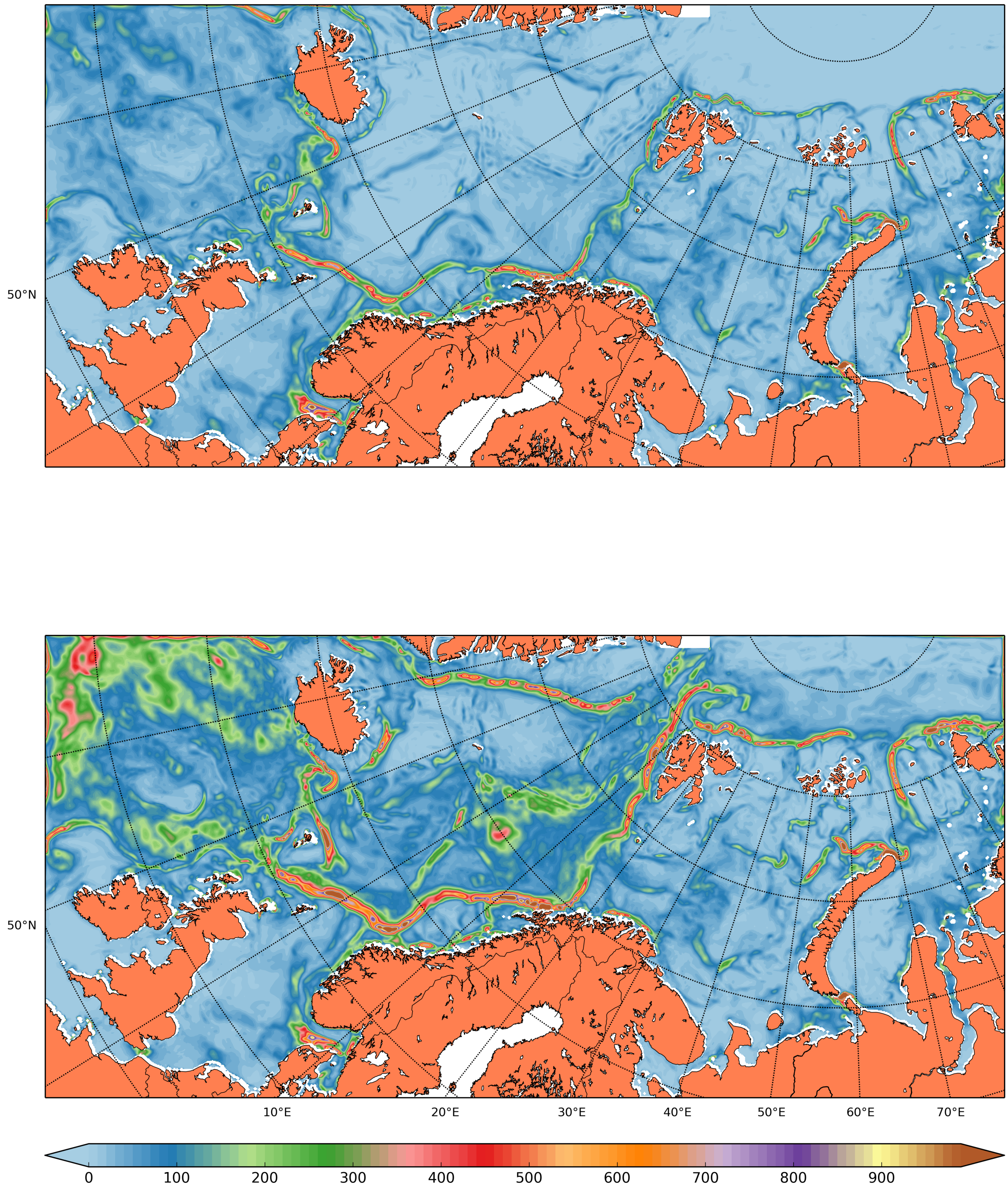

Figure 17: As Figure 1, but showing the TKE based on the barotropic currents extracted from a one year (1999) run using BaSIC4. Upper panel is *without relaxation*, while the lower panel is *with relaxation* toward's a montly mean SSS climatology. Note the enhanced energy levels in the lower panel when relaxation is turned on. Note also the presence of the Lofoten Basin Eddy (LBE) in the lower panel not present without relaxation (upper panel).

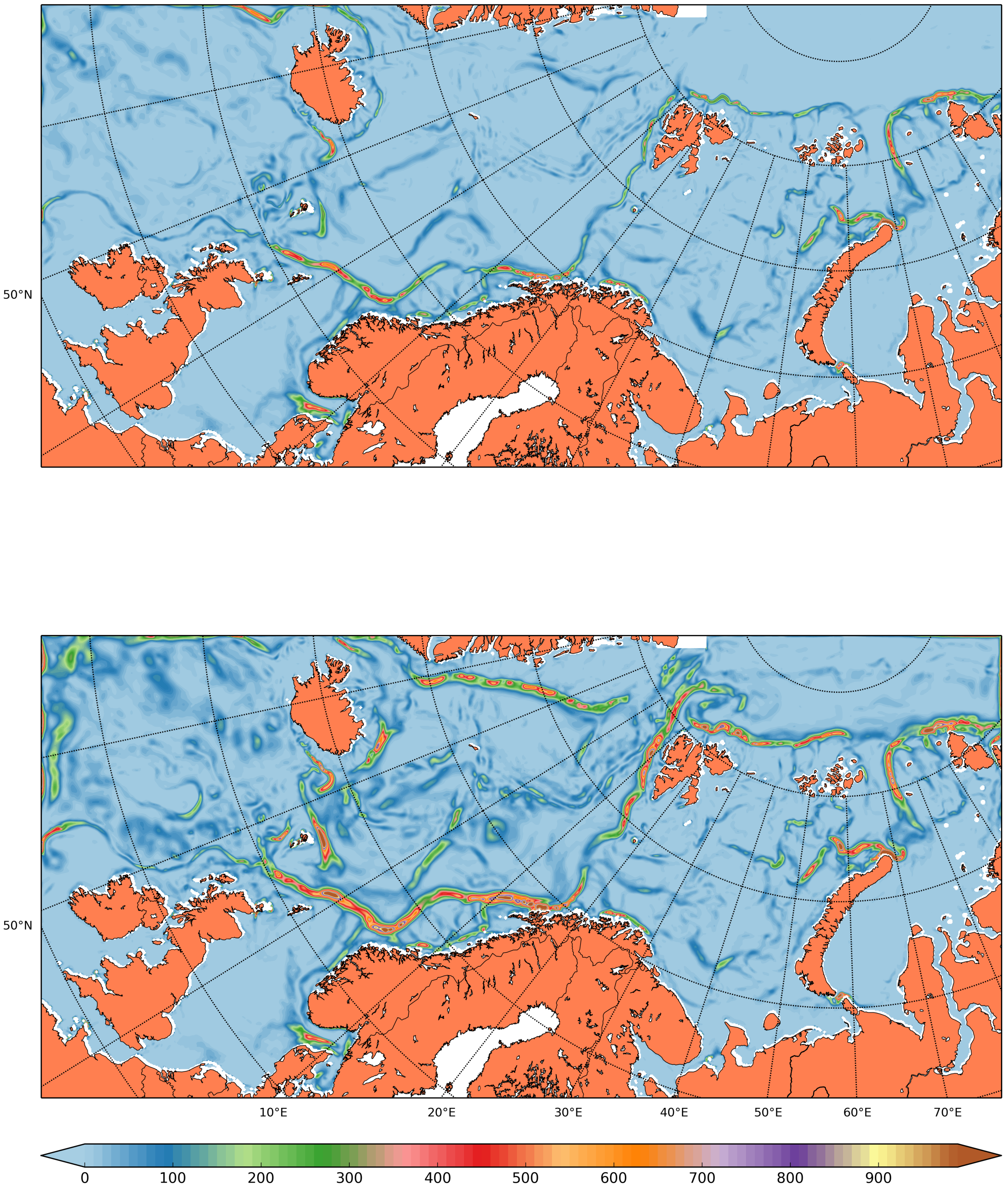

Figure 18: As Figure 17, but showing the mean kinetic energy (MKE). Note the presence of the LBE in the lower panel even in the one-year mean, which is an indication of the semi-permanent nature of the LBE. Note also that the LBE is missing in the upper panel when relaxation is turned off.

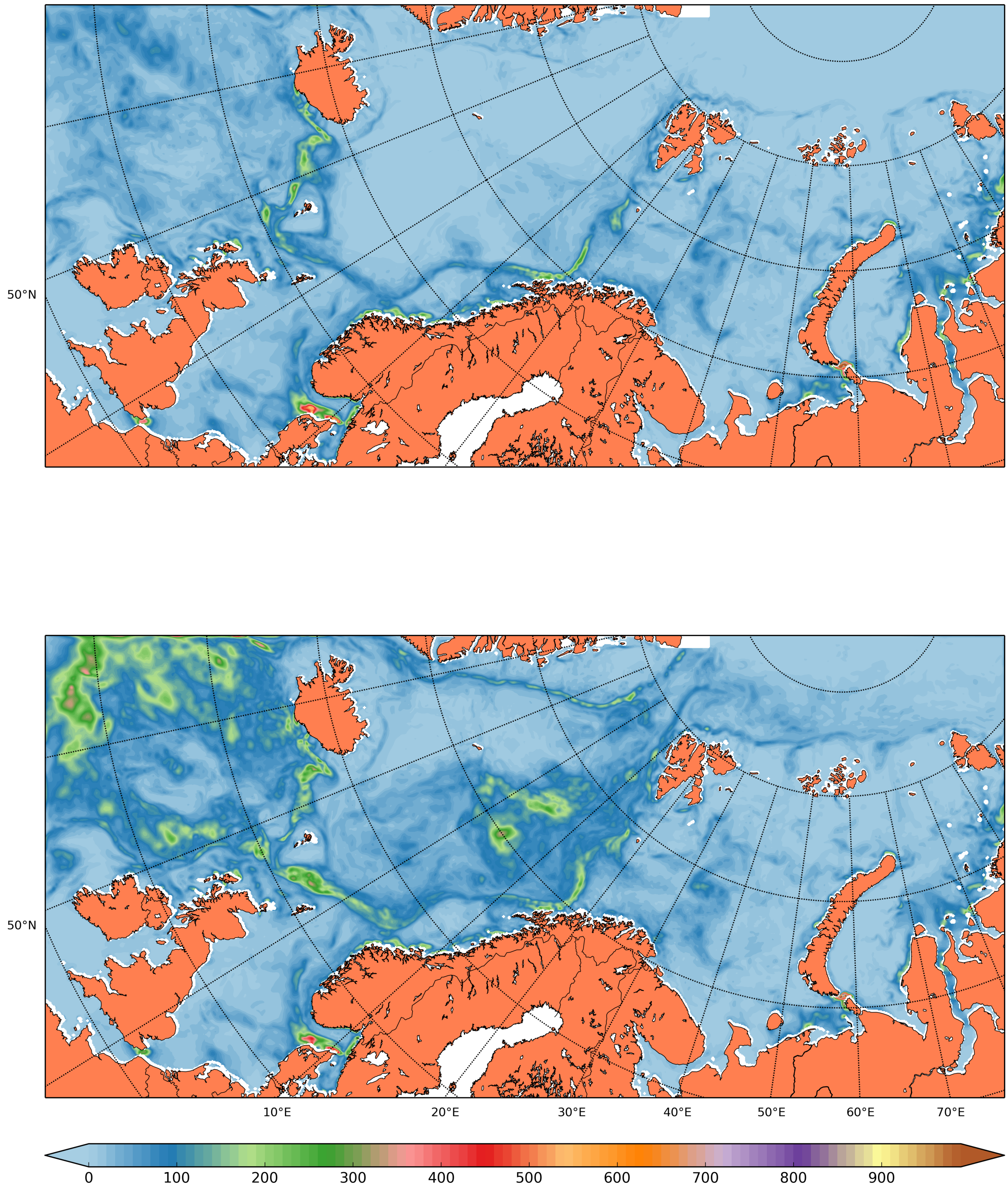

Figure 19: As Figure 17, but showing the eddy kinetic energy (EKE). Note the enhanced EKE in LBE area in the lower panel.

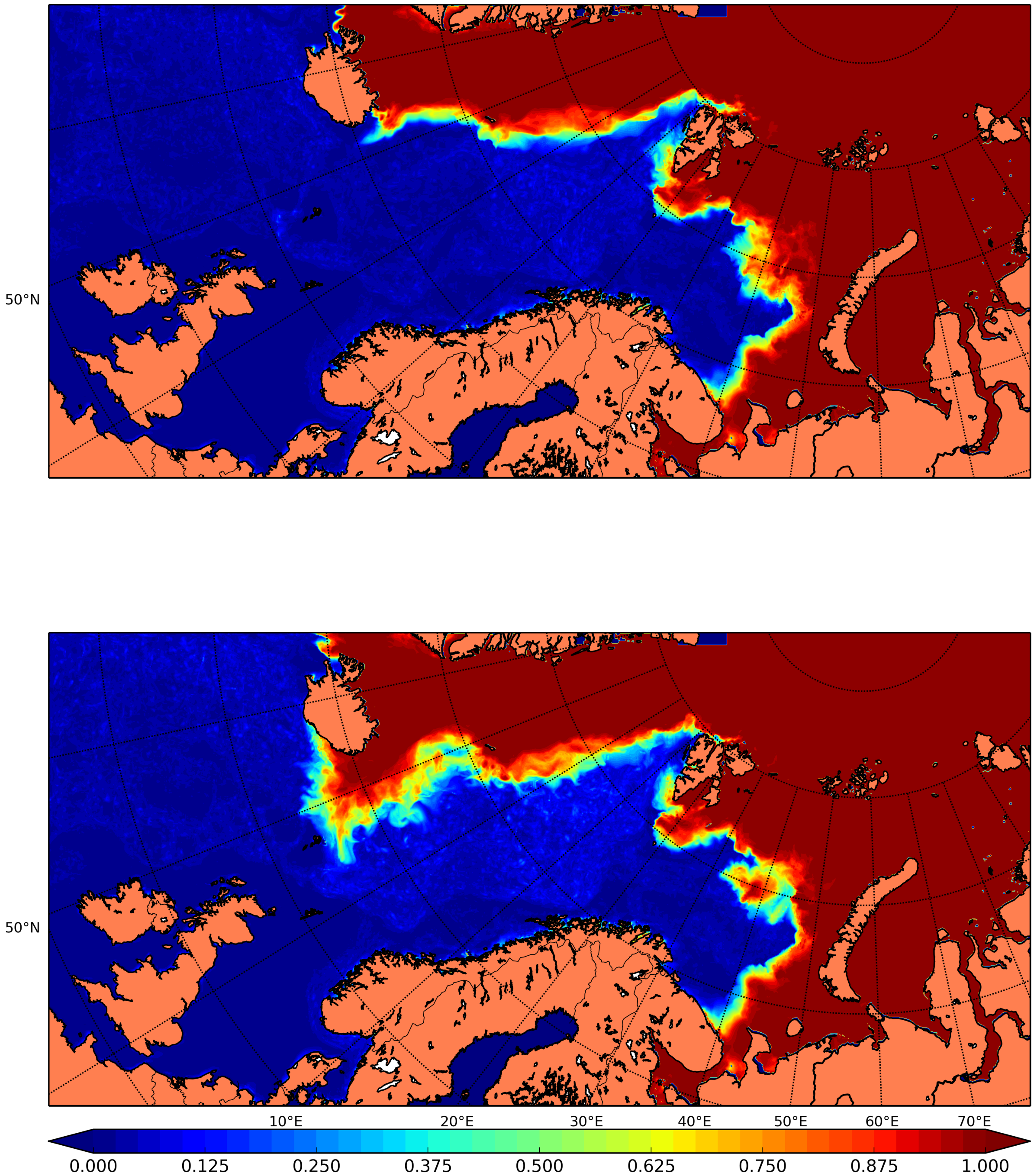

Figure 20: The maximum sea ice concentration as measured by the maximum ice concentration throughout the year 1999 at each position. Top panel is without relaxation toward's a mean monthly sea surface salinity climatology, while the bottom panel is with relaxation. Note that the presence of sea ice extending eastward toward the Faroes along the Iceland-Faroes-Scotland Ridge, in particular when relaxation is turned on. Note that the Barents Sea appears to be more or less unaffected by turning on relaxation.

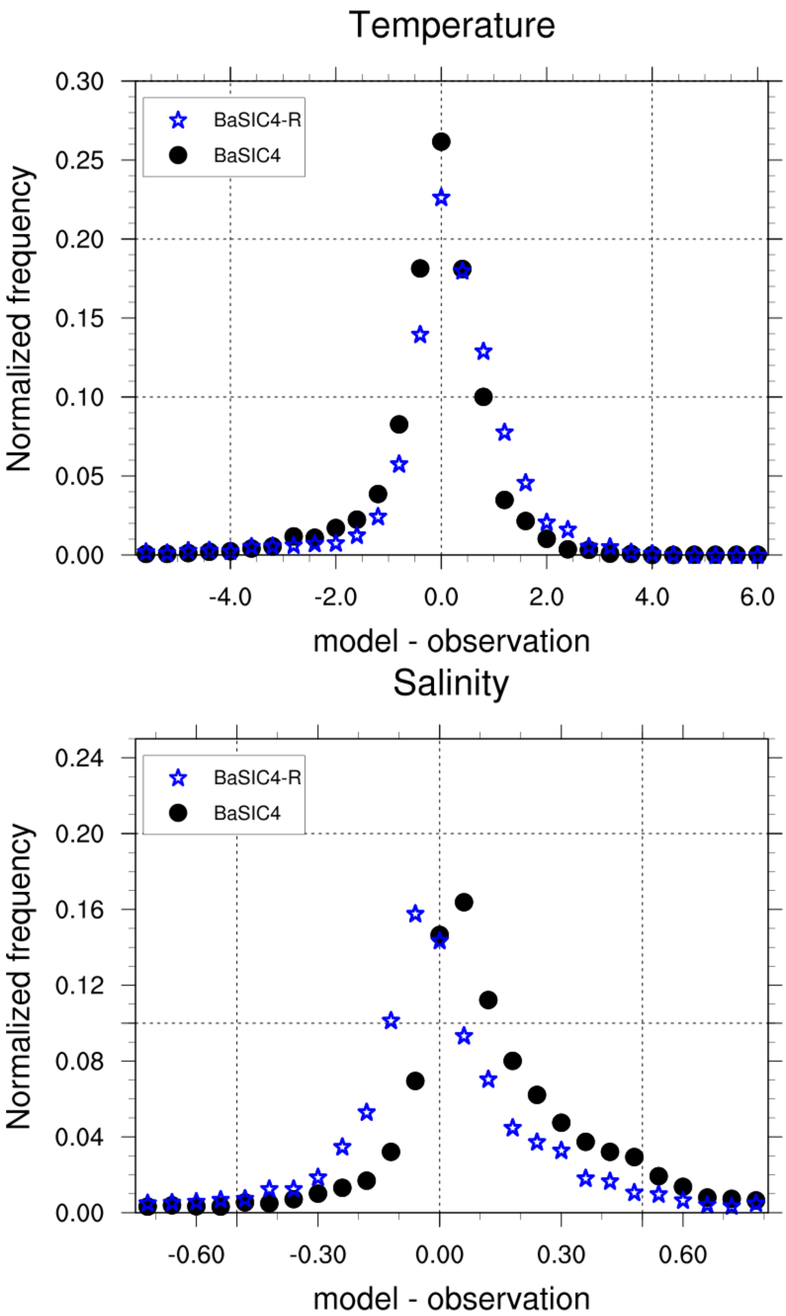

Figure 21: As Figure 10, but showing results for the one-year (1999) run using BaSIC4. Black filled circles are with relaxation *turned off* (referred to as BaSIC4), while the blue stars show the results when relaxation is *turned on* (referred to as BaSIC4-R). The biases are -0.10 (BaSIC4) and 0.13 (BaSIC4-R) for temperatures and 0.14 (BaSIC4) and -0.01 (BaSIC4-R) regarding salinities. The standard deviations are 0.99 (BaSIC4) and 1.26 (BaSIC4-R) for temperatures and 0.52 (BaSIC4) and 0.53 (BaSIC4-R) for salinities.

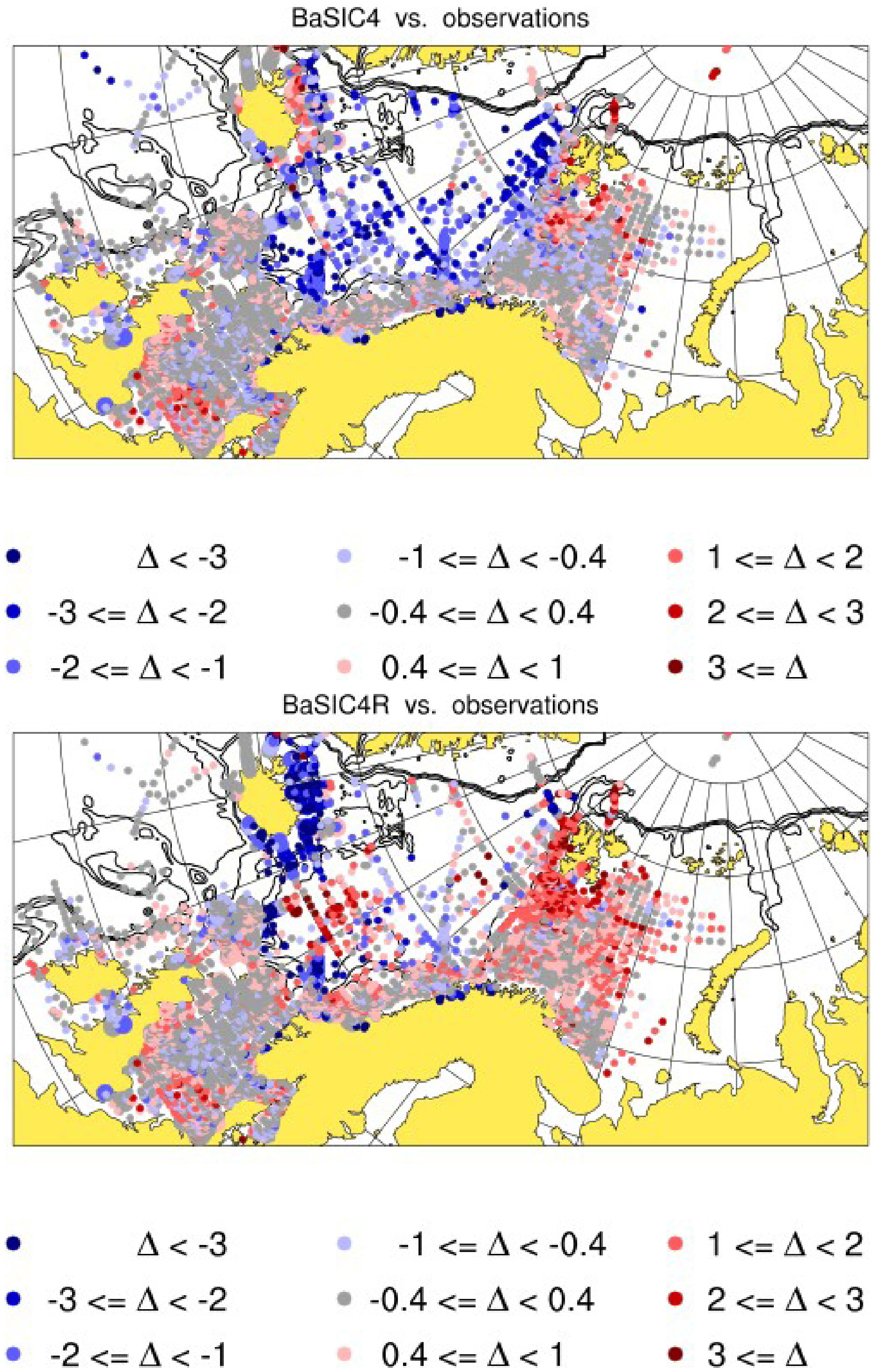

Figure 22: As Figure 11, but for a one-year (1999) run using BaSIC4. Upper panel is without relaxation (marked BaSIC4), while the bottom panel is with relaxation turned on (marked BaSIC4R). Note that turning on relaxation toward's a monthly mean SSS also have an impact on the sea surface temperature (SST).

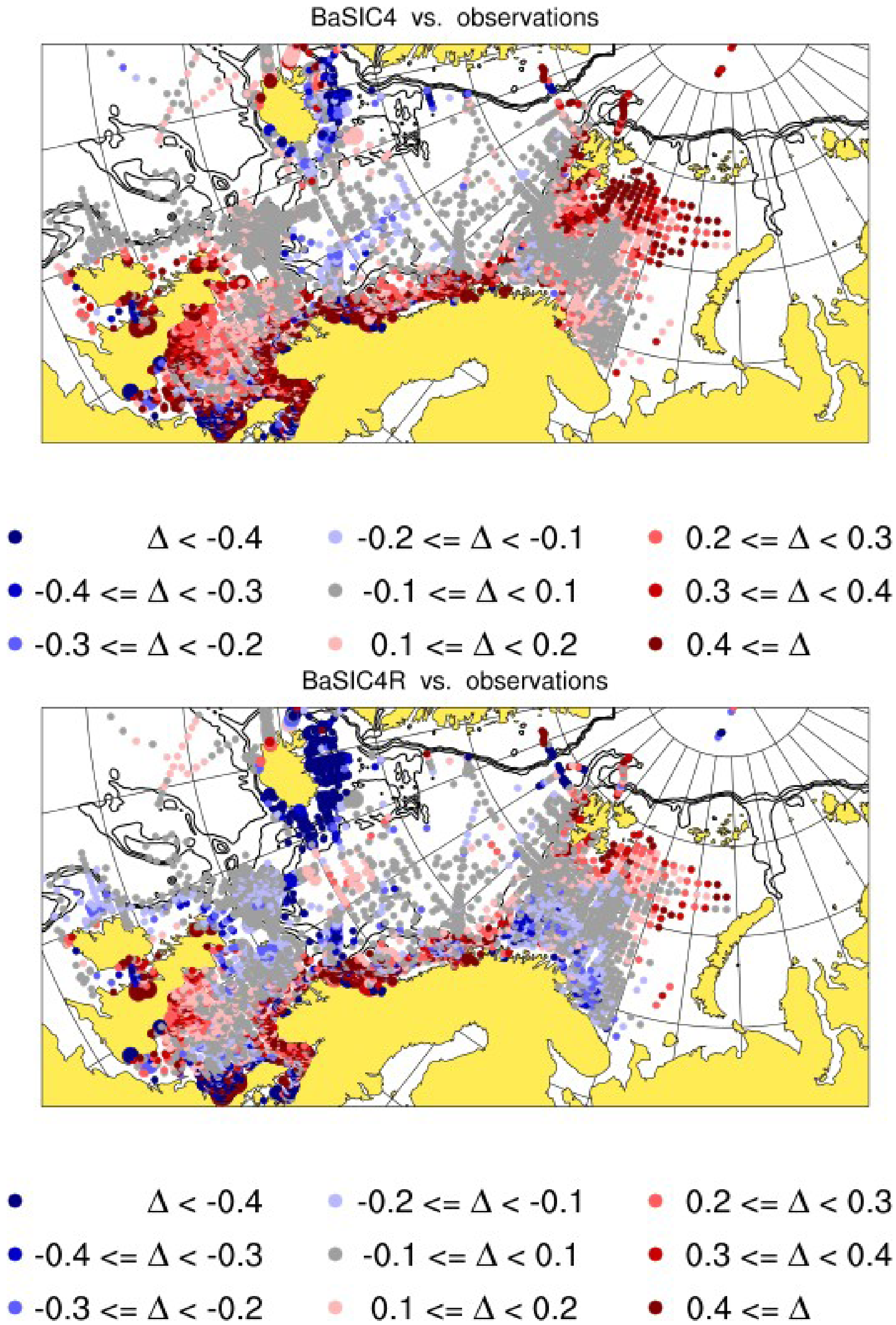

Figure 23: As Figure 22, but showing salinity. Note the improvement in most areas. It should be emphasized though that the monthly mean SSS climatology used here is preliminary. The results are shown to undescore that relaxation toward's a monthly mean SSS climatology do have an impact.

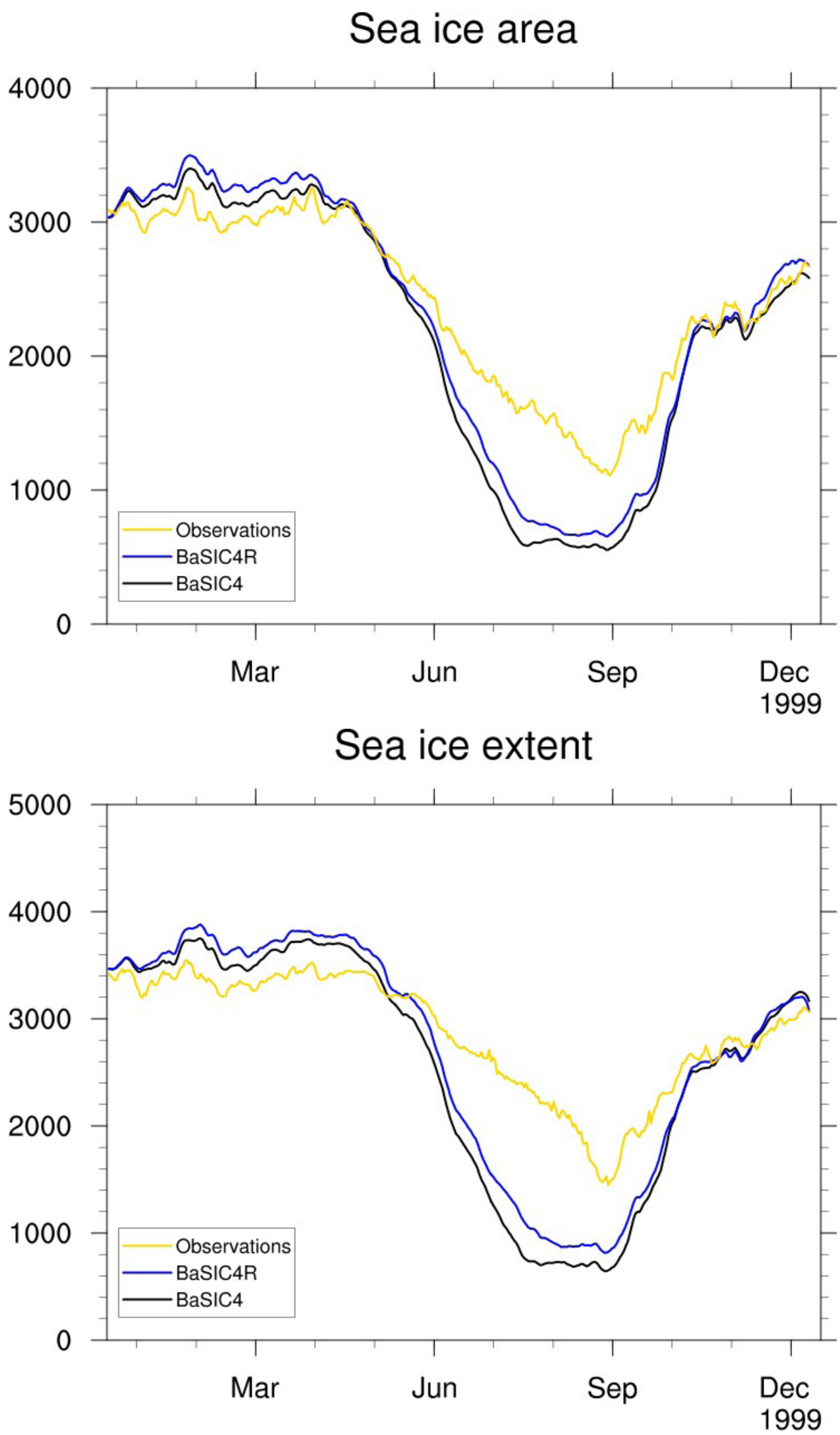

Figure 24: As Figure 15, but for the one-year period 1999. Observations are displayed by the yellow line. Black solid line referes to a run with relaxation *turned off* (marked BaSIC4), while the blue solid line line is with relaxation *turned on* (marked BaSIC4R). Overall averages (in 1000 km^2) regarding area are 2400 (Obs), 2170 (BaSIC4) and 2260 (BaSIC4-R), while the similar numbers for sea ice extent are 2860, 2560 and 2680, respectively.