Ocean Sci. Discuss., 7, C751–C769, 2011
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Ocean Science Discussions

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Interactive Comment

Interactive comment on "The effect of tides on dense water formation in Arctic shelf seas" *by* C. F. Postlethwaite et al.

C. F. Postlethwaite et al.

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Received and published: 14 February 2011

We thank the reveiwer for their constructive comments (shown in quotes).

I. General comment

"The manuscript presents results from a regional ocean model of the Barents Sea. The distinctive and novel feature of the model is an implicit description of the barotropic tides. The manuscript addresses effects of ocean tides on the sea ice and ocean stratification in the Arctic Seas. Overall, the study offers the insight in the role of tides in the Arctic. The manuscript covers topics relevant to the scope of the Ocean Science journal. Although the manuscript is carefully written, some aspects of the text needs improving (please see detailed comments below). The reviewer suggests that the manuscript should be published after addressing the comments.”

-No comment required.

II. Specific comments

1. Introduction

“Page 1670. Lines 24-25. “In general, global climate models do not explicitly. . .”. This statement is only partly correct. Some OGCMs do not include tides, however some do (please see the next comment). On the other hand, OGCMs forced with 6-hourly winds do simulate inertial oscillations, AKA high-frequency oscillations.”

-The statement has been left unchanged as, although some climate models do/can include tides, most do not. However, the introduction has been amended so that it now points to some of the climate models and OGCMs that do include tides (see supplement os-2010-40-supplement.pdf).

"Lines 25-26. The title of the paper promises ocean analysis, whereas the sentence refers to the impact on sea ice only. You may consider: “In this paper we consider an impact of tides on sea ice cover and ocean stratification in the an Arctic shelf sea region (Barents Sea) as simulated in the high-resolution regional OGCM.”"

-We agree the original did not fully reflect the scope of the paper and the revised manuscript has been amended.

“Page 1671. Lines 4-12. Please consider separating resolution and frequency of forcing issues for example as: “Nevertheless, the horizontal resolutions of ocean climate models, such as those that contributed to the IPCC AR4 (Randall et al., 2007) are still too coarse (_XX km) for tides to be appropriately captured in them. For example, a 200m deep shelf sea at 75_N has a barotropic Rossby radius and M2 tidal wavelength of about 315 km, requiring at least ∼100 km resolution. Besides, the typical frequency of atmosphere-ocean coupling of _YY days in IPCC-type models precludes the correct forcing of ocean tides.“”

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-This has been amended for clarity

“Lines 9-12. Statement: “Although model and computer advancement means that horizontal 10 and vertical resolution are increasing in OGCMs, regional models are for the moment the only ones that can regularly operate on finer resolutions and shorter time steps, allowing the explicit inclusion of the barotropic tide” is inaccurate. At present there are at least four published global OGCMs successfully running with explicit tides [1-4, see references at the end of the comments]. Please correct.

-We have changed the sentence to reflect that some OGCMs can now explicitly include tides.

“Lines 20-24. You may consider a more recent reference to the measurements of the mixing under sea ice [5].”

-We agree that this is a relevant reference.

“From line 29. “Although leads are not large (at most a few hundreds of meters in width)” – leads could be as 5-6 kilometers wide [6]. Please correct.”

-This has been changed in the revised text.

“Page 1672. Line 3. Please consider: “Interactions between tides and sea ice are shown schematically in Fig. 1.”

-We have removed “potential” from the sentence above. It was originally included to reflect that not all of the processes shown in the schematic will always occur.

“Page 1673. Lines 10-13. “Together with the Canadian Arctic Archipelago, the Barents-Kara Sea is the most tidally active region of the Arctic Ocean and so it is appropriate to focus our study in this area (Padman and Erofeeva, 2004).” This is a rather weak motivation. Please consider something along these lines: “The Barents Sea produces large quantities of dense water, tides are strong in the area (strongest in the Arctic, apart from the Canadian Archipelago) and play a significant role in dense water for-

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mation by affecting ocean stratification, circulation and sea ice." This would be more consistent with the paper title and analysis presented. You may also expand by saying that the Barents Sea is one of the most important Arctic regions: Atlantic water transformation, heat loss to the atmosphere, source region for the halocline and dense waters, etc. The references are in abundance."

-We agree that the reasons for choosing the Barents Sea needs more detail and the text now reflects this: ... we restrict ourselves to a 5 year regional model simulation of the Barents and Kara Seas. These seas are some of the most important in the Arctic, with the Barents Sea dominating Arctic Ocean heat loss to the atmosphere (Serreze et al., 2007) and the Kara Sea receiving ∼55% of the river discharge into the Siberian Arctic (Pavlov and Pfirman, 1995). Warm Atlantic water undergoes intense cooling in the southern ice-free sector of the Barents Sea producing dense waters that may contribute to deep water formation in the Arctic (Rudels et al., 1994; Schauer et al., 2002). To the north and east, brine rejection from sea ice and polynya activity also contribute to dense water formation (Midttun, 1985). Tides are strong in the Barents Sea (the strongest in the Arctic apart from in the Canadian Arctic Archipelago (Padman and Erofeeva, 2004)) and they play a significant role in dense water formation in the Arctic affecting stratification, circulation and sea ice.

"Please comment on the tidal studies utilizing imbedded sea ice [e.g., 7] and why you did not adopt this approach which has demonstrated the importance of the imbedded coupling to accurately simulate Arctic tidal motion of sea ice."

-In this study the sea ice is levitating as a pose to the more accurate representation of sea ice/ocean coupling using embedded sea ice. (Heil and Hibler 2002) highlighted the advantages of this approach and found that embedding improved the simulation of tidal and inertial ice motion. To embed a sea ice model into a free surface OGCM with a barotropic/baroclinic mode split algorithm requires merging the ice momentum equation and the barotropic momentum equation into a new "barotropic" equation in which surface pressure gradients and the divergence of the ice internal forces play a similar role (Hibler, Roberts et al. 2006). The introduction of this modification would have required a significant coding investment that we were not in a position to make. We acknowledge, however, that an embedded model would have been a more realistic choice.

"Overall, the introduction could be improved. The first paragraph needs more focus. Is the discussion of the Arctic sea ice decline relevant to the study, i.e., to the modeling of tides? If yes, please make it clear, e.g., tides increases simulated winter ice volume, etc."

-Yes it is relevant as the IPCC AR4 models could not capture the recent decline of Arctic sea ice. The absence of tides from these models may have contributed to this. However, this paragraph has been removed to make the introduction more focused.

"The statement “Sea ice is likely to play a crucial role in the formation of dense and intermediate water. . .” needs clarification. Dense and intermediate water formation where – on the Arctic shelves? Then please elaborate in the text how the Arctic shelf waters, Arctic dense and intermediate waters affect the global overturning. If this is about convection in the Labrador Sea, then it also should be explained. The next sentence “The realistic representation of sea ice in global climate models. . .” is confusing. Please be more specific what sea ice processes you are referring to and how these are related to the subject of your study.

The introduction should explain the motivation of the study, for example, (1) tides are important for sea ice and ocean, i.e., mixing, enhanced ice formation and associated increased brine rejection, and residual tidal currents, (2) climate models do not simulate tides explicitly because of the coarse resolution and large timestep and (3) Global OGCMs do include tides but require substantial computational resources to run. Therefore, regional models serve as an excellent option to study effects of tides in the area of interest, especially when sensitivity studies of model physics are required. Currently the second paragraph of the introduction is not well structured: it starts from climate

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models, then discuss OGCMs, then back to climate models, then back to OGCMS again."

-The introduction has been restructured to reflect these suggestions (please see os-2010-40-supplement.pdf for these changes).

2. Model description

“Page 1674. Line 2. “. . .and sophisticated ice ridging scheme.” – if this is important for the study please say more about the ridging scheme and why it is important, otherwise please delete.”

-The reviewer is correct that the ridging scheme is not used in this study and so should not be mentioned.

“Please also specify whether the ice model includes land-fast ice representation, if not please comment how it affects your results, as the substantial part of the regions under study is covered in winter fast ice [e.g., 8]. “

-There is no representation of landfast ice in the model. However, in the Pechora Sea the band of fast ice is relatively narrow and it is only in the Eastern Kara Sea that the fast ice is more extensive. This region is the least affected by tides in the model. The presence of fast ice in the model would mean that any polynyas caused by offshore winds would occur further away from the coast. In the Pechora Sea, this could mean they occur in less tidally energetic regions and hence would be less prone to the tidal effects described here. A note to this effect is now included in the conclusion.

“How does sea ice interact with tides in the model, e.g., through the residual tidal currents and ocean surface tilt? Please explain in the text.”

-Sea ice dynamics is affected by the tides through changes to the ice/ocean stress caused by the tidal currents and residual circulation. Sea ice thermodynamics is affected by the tides due to tidal mixing changing the ocean/ice heat flux.

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“Lines 7-16. The description of the model grid is confusing. First, it states that the model is on a polar stereographic grid, then in the next paragraph it is said that Cartesian coordinates are used. Has the polar stereographic grid been remapped on a Cartesian grid? Please explain in detail how the model grid has been constructed. What do you mean “. . .polar stereographic grid which allows each grid box to cover the same area with a resolution of 25 km in both directions.”? Polar stereographic projections do not preserve area, i.e., two equal-size regions on a sphere have different areas on a polar stereographic map. Consequently, distances are not preserve: equal distances on a sphere are of different length when projected on the map. “

-We agree there was ambiguity in the description of the grid. The revised manuscript now contains the following description: Both ocean and sea ice models are constructed on a grid defined using a Cartesian coordinate system (x,y) with the origin at the North Pole, the x-axis in the direction of 90°E and a resolution of 25 km in both directions. This is similar to the coordinate system described in (Gjevik and Straume, 1989) but has the geometric scale factors associated with moving from a sphere to a Cartesian plain as constants. The domain spans 0° E - 110° E and from 64° N – 84° N.

"Line 20. Please correct to “Six hourly fields of 2-m atmospheric temperature, pressure, humidity, 10-m wind velocity. . .”"

-This has been amended in the revised manuscript.

“Line 23. Is this climatological or 2000-2001 annual cycle of precipitation? Please clarify.”

-This was climatological and has been clarified in the revised text.

“Lines 24-26. Please clarify whether initial conditions for Sept 2000 have been used. Page 1675. Line 1. “. . .grid over a relaxation zone of width 100 km.” – is this around the lateral boundaries? Was any restoring applied in the domain interior? Please clarify.”

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-Yes, yes and no. The revised text now makes this clear.

3. Results

“Page 1676. Lines 10-12. Tidal ellipses in Figure 3b are not discussed, please consider either commenting the results or removing the figure. The correspondence in the amplitude between the model and observations is good; is the phase correspondence also good? Please comment.”

-A sentence describing where the M2 tidal velocities are intensified has been added to the revised text which refers to figure 3b. The phase correspondence is not as good, the rms = 43 degrees and mean deviation =6 degrees. This has also been added to the revised text.

“Page 1677. Lines 7-10. “It is unclear whether these . . . in the model or bulk formulae.” – there other possible causes are: the spread of the warm surface waters northwards, errors in parameterising ocean heat flux towards sea ice base, ice drift errors, ice is too thick at the end of the winter, the fact that 5-year spin-up with the repeated 2000-2001 forcing has been used establishing a bias state of the ocean and sea ice."

-We acknowledge that these are all plausible causes of the temperature offset at this location in the model. We had previously bracketed the first four of these together under the description of model deficiencies. We have incorporated the suggestion regarding a bias due to repeating years 2000-2001 in the revised text.

"Lines 15-16. “. . .has been divided into five subdomains defined by geographic and bathymetric boundaries.” – please explain what bathymetric criteria were used for the regions.”"

-These subdomains are the White Sea, the Pechora Sea (< 100m), the Kara Sea, the oceanic area around Svalbard (< 200m) and the rest of the Barents Sea (<400m). The revised manuscript now contains this information.

"Line 28.” Warmer sea surface temperatures. . .” – please explain what causes this, enhanced mixing due to tides, change in the circulation?"

-This is due to the enhanced vertical mixing caused by the tides bringing warmer water to the surface. Without tides, haline stratification supports cooler water overlying warmer water. With tides included in the model, this warmer water gets mixed to the surface earlier in the year. This is now explained in the revised text.

"Page 1678. Lines 5-8. “Although small, these oceanic heat flux anomalies are on the order of 10–20% of the net oceanic heat flux into the ice in the area and commensurate with ocean-sea ice heat fluxes in the central Arctic (Fichefet and Maqueda, 1997).” – the statement is unclear. Mean values of the heat flux in the central Arctic are compared to the changes due to the enhanced tidal mixing in the shelf seas where stratification of the water column and mixing rates are different. What is the conclusion?"

-The oceanic heat flux for the central Arctic was given as a reference to illustrate the point that a few W/mˆ2 is not necessarily a negligible figure by Arctic standards. However, we agree that this statement is unclear and it has been removed from the text.

"In general, the 1-3 W/m2 increase in the oceanic heat flux and a relatively small decrease in ice volume in summer, especially near Svalbard (_5%) (Fig. 6e) is surprising, considering measurements are evident of a 10-50 fold increase of the oceanic heat flux due to tides [9]. Perhaps, such a moderate impact of tides on the ice melting could be explained by shortcomings of the ocean-to-sea ice heat flux scheme used in CICE. Magnitude of the ocean-to-sea ice heat flux as well as its sensitivity to the tidal mixing would depend on the choice of the heat flux parameterisation, thus the impact of tides on sea ice cover might be different if another scheme is used. Please comment."

-As mentioned in the text, the ice volume in the Svalbard subdomain is strongly influenced by the boundary conditions. Tides increase the volume of ice advected into the Svalbard region from the northwest. Thus Fig 6e does not really tell us anything about changes to ice melting. The net annual melting is shown in Table 2. Svalbard has 8%

more melting with tides when integrated over the year (During the summer period this is more like 10-20% more melting with tides). McPhee (2003) describes a 10 fold enhanced heat fluxes over the Yermack Plateau compared to deeper surrounding areas and notes the strong tides at that location. The Yermack Plateau is not within the 400m shelf sea limit we prescribe and as such is not discussed in the manuscript. However, both model runs described in the manuscript have similar heat fluxes to that of McPhee (2003) over the Yermack Plateau, with the tide run having a small increase. The proximity of this location to the model boundary precludes us making any comparisons with these results in the text.

-The change in oceanic heat flux between the tides and no tides simulations should be large, but is not. This is consistent with the observation that changes in ice volume are small, but somewhat disconcerting. The reviewer suggests an ice/ocean coupling problem. That might well be the case, but I would expect the upper ocean to heat up in the tides case if it were not losing heat at the right rate. If most of the region is already well mixed in the no-tides case, the addition of tides might not have a great impact on oceanic heat fluxes.

4. Discussion

"Page 1680. Lines 16-17. ". . .in the model, snow falling on ice does not enter the ocean until the ice melts," – is this right? CICE v3.14 Documentation (Hunke and Lipscomb, 2006) describes direct snowmelt input into the ocean (page 4) as well as deposition of snow to the ocean during ice ridging (page 22). Please check."

-The reviewer is correct. Surface melting and ridging will allow snow to enter the ocean. The original comment referred to the fact that snow cannot be melted by the ocean until the underlying ice has melted. The sentence now says "in the model, snow falling on ice does not enter the ocean until the snow melts or ridging occurs".

"Page 1680. Line 25 and Figure 9a,b. "The distribution of this parameter is dominated by the water depth and there is therefore very little difference between the winter and

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summer plots.” Figure 9a,b has a cap on the range of values of 10ˆ4 kg/m2, thus the reader cannot see any pattern dominated by depth, except the shallow areas; the plot needs logarithmic scale. A better diagnostic to illustrate annual cycle might be a depth integrated salt content, weighted by the depth and by the area (it is a mean salt content of the water column)."

-The figure has been replotted on a logarithmic scale to address this.

"Page 1681. Line 22. Figure 10. Definition of the Shallow Pechora Sea and Storfjorden regions should be included here."

-This has been amended in the revised text

"Page 1682. Section 4.1.1. Figures 8 and 9 show changes in the ocean velocity fields, some of these could be attributed to the changes in horizontal gradients of salinity, i.e. density. It would be worth discussing changes in the ocean circulation due to tides."

-The reviewer is correct that the tides can affect the circulation by both tidal rectification and changes to density. However the analysis presented here cannot distinguish between these two and further analysis would be required such as in (Holt and Proctor, 2008). Please note that there is a description of changes to circulation within section 4.1.3 during discussion of sea ice export. This has been amended to make it clear that we are uncertain whether the residual circulation is tidal rectification or density driven.

"Page 1684. Line 4. Kara Gate, not Kara Strait. Please correct."

-This has been amended in the revised text

III. Technical corrections

"Page 1674. Lines 6-7. “These are discussed in Sect. 2.3 along with the surface forcing used.” – there is no such a section, should be Section 2.1. Please correct."

-This has been corrected in the revised text.

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"Page 1677. Lines 26-27. “The impact of including tides in the model on the sea ice area and volume varies between subdomains (Fig. 6b and d),. . .” – should it be Fig.6c,e?"

-This has been corrected in the revised text.

"Page 1679. Lines 11-13. “The salty Atlantic Norwegian Current. . .” – It is the Norwegian Atlantic Current; “One branch enters the Barents Sea following the Norwegian coastline. A second branch continues northward, tracking the continental slope.” – the first branch is called the North Cape Current, the second branch is called the West Spitsbergen Current; please use the commonly accepted names [10]."

-The revised text now contains the commonly accepted names.

"Lines 17-18. “..entering the eastern Barents Sea between Novaya Zemlya and Severnaya Zemlya (Fig. 7). ” – this is incorrect. From [11] eastern limits of the Barents Sea are: “Cape Kohlsaat (Franz Josef Land) to Cape Zhelaniya (Novaya Zemlya). . .”. Any section Novaya Zemlya-Severnaya Zemlya is in the Kara Sea. Please correct."

-The revised text now uses the correct limits for the Kara Sea.

References

"Hunke and Lipscomb (2004) – CICE v3.1 not v3. Please correct."

-This has been corrected in the revised text

Figures

"Please use either “Fig. XX” or “Figure XX” through the text."

-This has been amended in the revised text.

"For all geographical plots please add longitude lines at 30 and 60 degrees east. Also, latitude numbers should be outside the plot area; they are not readable in Figs. 8 and 9 and totally obscured in Figs 3a and 7. Please also consider rotating all geographical

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plots 45 deg clockwise and resizing the images to have a less land area."

-Extra longitude lines have been added to the plots. Latitudes have been moved so they are more legible. The figures have not been rotated as the current orientation is that of the Cartesian grid the model was run on. However, the figures have been cropped so there is less land. The editing team has assured us the figures can be made larger if necessary. Please note that the automatic scaling of the figures used for on-line publication does not represent the size of the final figures.

"Figures 10a,b,c,e are not referred to. Please check the order of figures citation."

-This has been amended in the revised manuscript

"Figure 1. New ice is hard to see on the schematic. Please increase the pattern contrast."

-The figure has been amended (see response to A.Turner for revised Figure 1).

"Figure 2. Please make gauge positions more visible by making dots larger and moving around geographical names. 300-m depth contour is needed in 2b. Please fill the land grey in 2b, the bathymetry contours are difficult to see."

-The gauge positions have been enlarged. Figure 2b has been amended to include extra bathymetry contours, the land has been shaded grey and it has been combined with figure 6a to show subdomain boundaries. See Revised Figure 2 at end of text.

"Figure 3. Fig 3b doesn't work: ellipses are too small in the central Barents Sea. Please consider rearranging the plates vertically. Please consider changing the caption as: "Fig.3. (a) Contour plot of the M2 tidal elevation amplitude in meters (colour with black contours) and phase in degrees (white contours); (b) M2 tidal ellipses." Please adjust the limits of amplitudes to see more structure in the Barents Sea."

-No changes to the tidal ellipses have been made as increasing the size would cause the larger ellipses to overlap. The whole figure will be enlarged if necessary. The colour

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scale and contour frequency for tidal amplitude has been changed on figure 3a to give more structure in the central Barents Sea. The amplitude contours are now spaced every 10 cm from 0 – 1m and every 50 cm from 1-3 m. The caption has been changed. See Revised Figure 3 at end of text.

"Apparently figure 5c is of a low resolution and fuzzy, please replace with a high resolution version."

-Figure 5c has been replaced with a high resolution version.

"Figure 6a is too small. It would be better to combine 6a with Figure 1b."

-Figure 6a has been combined with figure 2b

"Figures 7-9. Vectors are unreadable. Please consider (a) rotating 45 deg clockwise and resizing the images to have a less land area, (b) to have two plates per figure, arranged vertically with a single colour bar, (c) making depth contours a different colour from vectors, possibly light-grey and (d) making vectors longer. Limits on salinity should be adjusted to see the structure in the bottom fields; perhaps a non-linear scale is need. Number of bathymetry contours in the Barents Sea is inadequate; additional contours at 200 m and 300 m depth are need."

-Figures have not been rotated (see above) but land area on plots has been reduced. Bathymetry contours are now grey. The vectors have been enlarged and the final figure will be larger. Salinity scale has been changed to see more detail. An additional bathymetry at 200m has been added (adding 300m made the plots too cluttered). See Revised Figure 7 at end of text for example of how the figures have been changed.

"Figure 7, caption. Please consider editing as: "Mean sea surface salinity and velocity for (a) winter and (b) summer from the fifth year of integration of the control model run.""

-The caption has been changed

"Figure 9, caption. Are the plates (a) and (b) from the control run or tidal run? Please

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specify in the caption."

-These are from the control run. This is now specified in the caption.

"Figure 10. There is no definition of the Shallow Pechora Sea and Storfjorden regions in the text. The definitions of those should be included in the text and in Figure 10 caption."

-The definition of these regions are now included in the text.

"IV. References for the comments [1] Arbic et al. (2010). Ocean Modell. 32, 175–187. [2] Muller et al. (2010). Ocean Modell. 35, 304-313. [3] Schiller and Fiedler (2007), Geophys. Res. Lett., 34, L03611. [4] Thomas et al. (2001). Geophys. Res. Lett. 28, 2457–2460. [5] Lenn et al. (2010). Intermittent intense turbulent mixing under ice in the Laptev Sea Continental Shelf, J. Phys. Oceanogr., in press. [6] Lindsay and Rothrock (1995). J. Geophys. Res., 100(C3), 4533– 4544. [7] Heil and Hibler (2002), J. Phys. Oceanogr, 32, 3029–3057. [8] Divine et al. (2004). Cont. Shelf Res 24, 1717-1736. [9] McPhee, et al., (2003). Geophys. Res. Lett., 30(24), 2274. [10] Furevik (2001). Deep-Sea Res. Part I 48(2), 383-404. [11] Limits of Oceans and Seas (1953). Internat. Hydrograph. Org., Spec. Publ. No 23, http://www.iho-ohi.net/iho_pubs/IHO_Download.htm#S-23. Interactive comment on Ocean Sci. Discuss., 7, 1669, 2010."

References for responses

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Serreze, M. C., Barrett, A. P., Slater, A. G., Steele, M., Zhang, J., and Trenberth, K. E.: The large-scale energy budget of the Arctic, Jounral of Geophysical Research, 112, doi:10.1029/2006JD008223, 2007.

Please also note the supplement to this comment:
http://www.ocean-sci-discuss.net/7/C751/2011/osd-7-C751-2011-supplement.pdf

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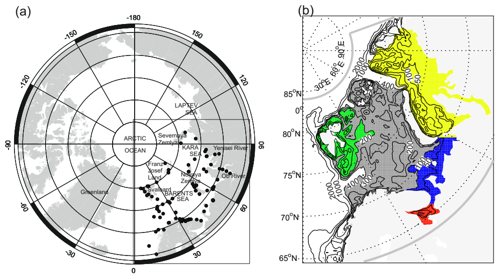

Figure 2.

Fig. 1. Revised Figure 2. (a) Polar stereographic projection of the Arctic showing the study region. Black dots indicate the location of tide gauges. (b) Bathymetry of the Barents and Kara Seas domain.

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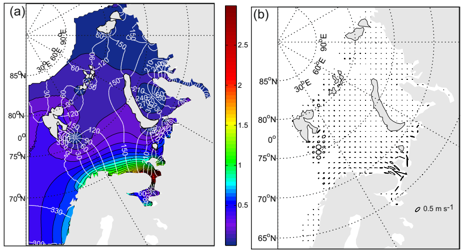

Figure 3.

Fig. 2. Revised Figure 3. (a) Contour plot of the M2 tidal elevation amplitude in meters (colour with black contours) and phase in degrees. (b) M2 tidal ellipses.

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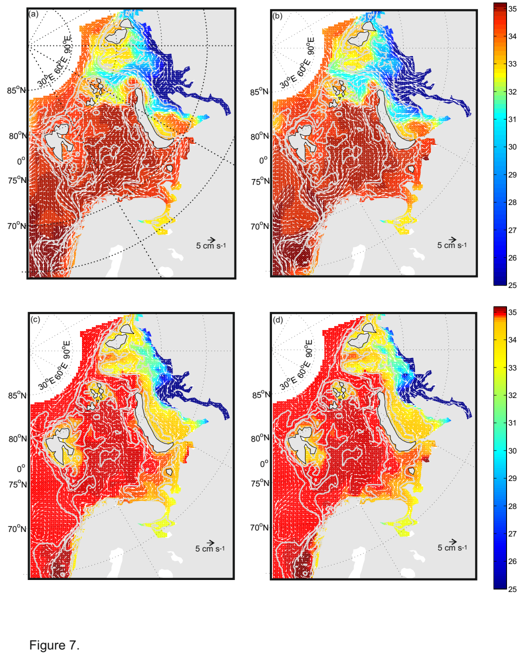

Fig. 3. Revised Figure 7. Mean sea surface salinity (color contours) and velocity (arrows) for (a) winter and (b) summer. Mean sea bottom salinity and velocity for (c) winter and (d) summer

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