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Ocean Science
Discussions

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

Anonymous Referee #2

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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.

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.

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."

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 ($\sim$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 $\sim$100 km resolution. Besides, the typical frequency of atmosphere-ocean coupling of $\sim$YY days in IPCC-type models precludes the correct forcing of ocean tides."

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.

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

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.

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

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 formation 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. 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.

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

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. 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]. 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.

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.

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

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

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.

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.

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.

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.

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

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 com-

mensurate 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? 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 ($\sim$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.

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.

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 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).

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

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.

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

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.

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?

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].

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.

References

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

Figures

Please use either "Fig. XX" or "Figure XX" through the 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

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

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

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

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.

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.

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

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

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.

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."

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

specify 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.

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.

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