Response to Reviewer

Guokun Lyu, Nuno Serra, Meng Zhou, and Detlef Stammer

We thank the reviewer for reading the manuscript carefully and providing detailed comments. We have improved the manuscript point-by-point according to the reviewers' advice. Below we respond to the reviewers' questions and suggestions with the key points highlighted in red.

Lyu et al. use two setups of MITgcm to investigate sea level variability of the Arctic Ocean on different time scales. Comparison with observations shows acceptable quality of model simulations that allow authors to look at different time frequencies of variability and specify main physical contributors. They proceed with an attempt to give an estimate of capability of the current observing system to monitor freshwater content variability.

The paper will be interesting for Arctic Ocean modelling and observational communities, and can be published after some moderate revision.

General comments:

[1] When you are talking about anomalies, please specify the time period of the reference mean.

Response:

We thank the reviewer's comment on the terminology "anomalies". We have clarified the anomalies throughout the manuscript.

[2] Overall, I would work on the general quality of the figures, especially ones with arrows on them. Most of them are hard to read.

Response:

We thank the reviewer for pointing out the problem concerning the figure quality. We have remade all the figures and made them more readable to the readers.

Minor comments:

[3] L71 Please provide more info on vertical grid spacing, especially in the upper levels.

Response:

We thank the reviewer's comment and added, "In the vertical, ATLARC08km has 50 levels with resolution ranging from 10 m over the top 130 m to 456.5 m in the deep basin. And ATLARC04km has 100 z-levels ranging from 5 m over the top 200 m to 185 m in the deep basin." (L77-79) to explain details of the vertical grid spacing.

[4] L78 Please identify the source of river runoff climatology

Response:

We thank the reviewer's comment. The source of river runoff climatology is from (Fekete et al., 2002) and is added to the revised manuscript (L85).

[5] L80-81 Please provide more details on the procedure of initialising the high resolution model from the low resolution fields. Which tracers are interpolated? Did you interpolate the velocity field as well?

Response:

We thank the reviewer's comment. We initialized the high-resolution (ATLARC04km) simulation from an initial condition, including velocity, temperature, and salinity. We added "ATLARC04km starts from the initial condition, including velocity, temperature, and salinity of ATLARC08km at the start of the year 2002" (L88) to provide more details on the initialization procedure.

[6] L81 Can you specify what variables are outputted (especially 3D ones).

Response:

We thank the reviewer's comment. We have output uvel, vvel, wvel, potential temperature, salinity, sea surface height, and all surface fluxes. In this study, we mainly use potential temperature, salinity, sea surface height, and listed them in Table 1. (L91)

[7] L106 Please define P_b

Response:

We acknowledge the reviewer for pointing out the missing definition of P_b, and added the definition "P_b' is the bottom pressure anomalies in equivalent meters of water." (L121-122).

[8] L142 I would say that the word "matches" is a stretch, especially for the Beaufort Gyre. The intercomparison results would be more convincing if you could provide some error estimates for observations. On the other hand from Fig.3 it is clear that the amplitude of variability is underestimated in the models.

Response:

We thank the reviewer's comment. Indeed, an error estimate of altimetric observations will make the statement more convincing. However, uncertainties of altimetric observations remain problematic due to the processing of altimetric data. As we have already noticed, the model usually underestimated the variability (Fig.3), and ATLARC04km simulated much stronger SLA variability, we state that "matches better with the observed sea level variability". We also discussed the Rossby radius in the Beaufort Gyre and explained the improvement of ATLARC04km due to increased resolution (L147-162).

[9] L154-155 "Relative more significant" → "Relatively stronger"? I don't think you mean significance in a statistical sense here, so better not to use this word to avoid confusion.

Response:

We thank the reviewer for pointing out the confusion, we have changed "relative more significant" to "relatively stronger" in L171-172.

[10] L156-157 I would love to see more support for this statement, for example a figure in the Support materials with Low/High-pass filtered data for frequencies you are working further (<30 days, seasonal cycle, decadal).

Response:

We appreciate the reviewer's comment. For the reviewer's information, we show in Figure R1 the processes of separating high-frequency and seasonal cycle of SLA using daily output of ATLARC04km and separating the decadal signals and seasonal cycle from the monthly output of ATLARC08km.

This process is only technical and one can separate signals with different timescales using various filters. To keep our idea straightforward in the study, we didn't include this part.

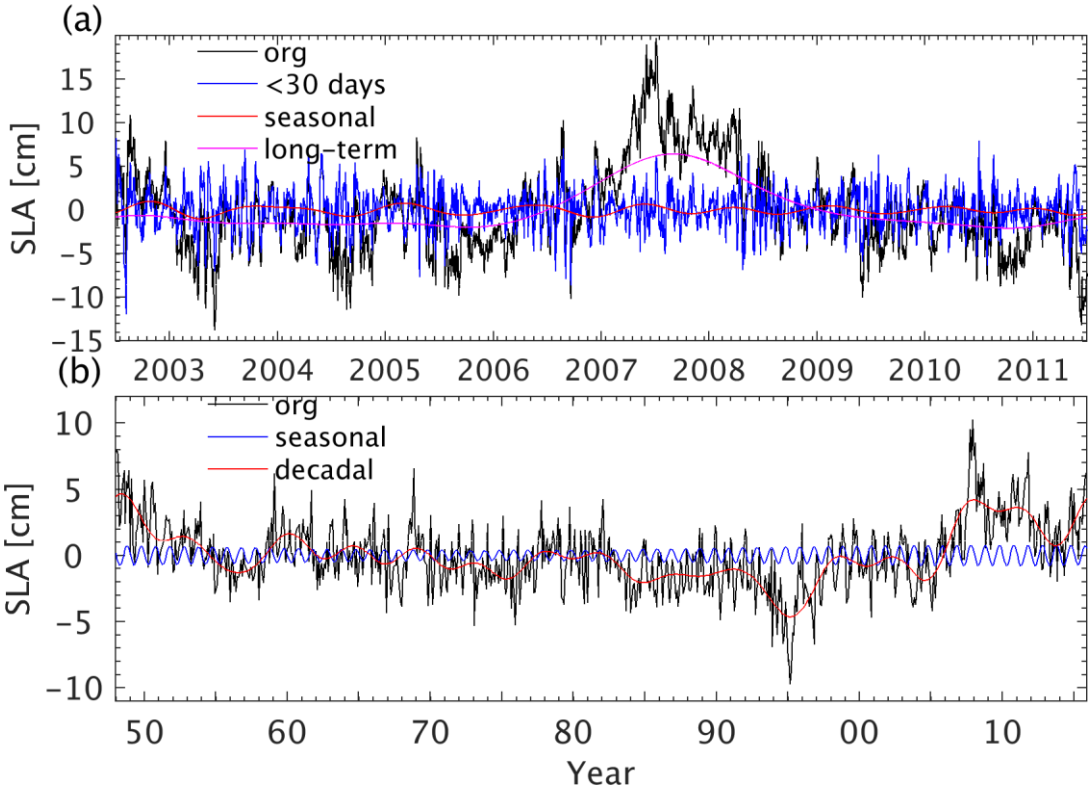

Figure R1. Timeseries of SLA (in centimeters) averaged over (a) the East Siberian Sea using daily output of ATLARC04km and (b) the Canadian Basin using the monthly output of ATLARC08km. The high-frequency signal (<30 days), seasonal cycle, and long-term signal is extracted and overlaid in panel (a). The decadal signal and seasonal cycle are also extracted using the monthly output of ATLARC08km and shown in panel (b).

[11] Fig 5. Letters A and B should be made bigger. Why 2004? Anything particular about this year?

Response:

We thank the reviewer's comment. We have remade Fig. 5 with big letters c and d (denoting panels c and d) in the sub-region. There is no specific reason for the choice of 2004. This is only a show case to display the baroclinic and barotropic nature of sea level variability as revealed by Figs. 5a and b

[12] L196-197 It is clear why you use NwAC box, but please justify the selection of the box in ESS (I guess it's close to maximum RMS variability, but this should be stated).

Response:

We thank the reviewer's suggestion. The reason for choosing a sub-region in ESS is because of its high variability and to show the barotropic nature of high-frequency variability. We have justified the sub-regions in ESS by "Subregions in the East Siberian Sea (c in Fig. 5a) near the maximum RMS variability and along the NwAC (d in Fig. 5a) are used to reveal details of the high-frequency sea level variability". (L214)

[12] L207 It is really hard to see anything on this figure, especially some correlation along 1000 isobath. The figure should be made much clearer. Or maybe just make it bigger.

Response:

We thank the reviewer's comment. We have revised Fig. 6 to make it clear for the readers and only show correlations with 95% significance level.

[13] L210-212 How should I interpret the correlation arrows? Is it the direction that has maximum correlation? What does the length of the arrows mean?

Response:

We appreciate the reviewer's comment. The arrows (u,v) are the correlations of SLA to the zonal (east/west) and meridional (south/north) wind stress. For instance, SLA increases in the East Siberian Sea (blue pentagon in Fig. 6b) favor anticyclonic (vectors in Fig. 6b) wind stress anomalies. The length of the arrows indicates the size of correlation coefficients and angles indicate correlations to wind vector. To clarify the gaps, we added reference vectors of "1" (correlation coefficient of 1) to each panel (top left side) to show size of the correlation coefficients (length of the vectors). We reproduced Fig. 6 and rephrased L220-234 to make the figure easier to understand by the readers.

[14] L213 I guess you mean A and B from Fig 5? Then I believe the pictograms on Fig. 6 do not coincide with placement of resigning on Fig.6, at least for the region A.

Response:

We have remade Fig. 6 to make the sub-regions clear. The two sub-regions are slightly different fromFig.5. These are examples to test relations of SLA to wind stress.

[15] Fig.6 You need to provide legend for arrows (maybe it's the arrow over Greenland, but it's not the proper place for the legend) and better explain how to interpret them. Magenta pictograms are practically invisible. Try using a pointing arrow, or highlight them in another way. Make sure the regions are right. Overall the figure is really messy and has to be made much clearer.

Response:

We thank the reviewer's suggestion on Fig 6. We have added the legend arrows to the left top of each panel and simplified Fig. 6. Besides, we reformulate L220-234 to give a better description and explanation of Fig. 6.

[16] Figure 8. Why 500m? Usually the boundary is set at 200 m.

Response:

The choice of 500 m or 200 m is arbitrary. The choice of 500 m in this study is that it can easily separate the marginal seas to the deep basin, especially the Barents Sea since large areas of the Barents Sea is deeper than 200 m. In addition, the Arctic continental shelf is very steep and using 500 m or 200 m criteria will not change the conclusion here.

[17] Figure 9. Anomalies with respect to what (specify time period)?

Response:

Here "anomalies" means anomalies to the climatology in ATLARC4km. We added "to the climatology" and "ATLARC4km output is used." (L298) to Fig. 9 caption to clarify which anomalies and which model simulation we used in this figure.

[18] L282-306 Does those results expand results of Koldunov et al., 2014, obtained earlier for the same time scales on the low-resolution version of the model? Or are they similar?

Response:

Actually, Koldunov et al. (2014) also used this ATLARC08km to demonstrate the decadal sea level variability and the relations to atmospheric circulation changes case by case (1987–1992, 1993–2002, and 2003–2009). This section summarizes the decadal sea level variability throughout 1948-2012. The conclusion is similar to the study of Koldunov et al. (2014) that "decadal sea level variability is determined mostly by salinity variations".

[19] Figure 11. Please put units on axes.

Response:

We thank the reviewer's advice. We have added ylabel and units to the figure.

[20] L377 Can you clarify how you distribute the profiles? Do you take positions and timing of realworld profiles (I guess so), or do some random sampling? One clarification sentence would be beneficial.

Response:

We thank the reviewer's advice. We generated synthetic observations using a "truth" state and positions and timing of "real" world profiles collected and compiled by Behrendt et al. (2018). Then we tested to what extend we can reconstruct the "truth" state and identify observational gaps.

We explained this process in L411-414: "Based on the spatiotemporal distribution of

profiles compiled by Behrendt et al. (2018) and an ensemble optimal interpolation (EnOI) scheme (Evensen, 2003;Lyu et al., 2014), we test to what extent the generated synthetic profiles could help to reconstruct the "true" state".

References:

Behrendt, A., Sumata, H., Rabe, B., and Schauer, U.: Udash – unified database for arctic and subarctic hydrography, Earth Syst. Sci. Data, 10, 1119-1138, 10.5194/essd-10-1119-2018, 2018.

Evensen, G.: The ensemble kalman filter: Theoretical formulation and practical implementation, Ocean Dynamics, 53, 343-367, 10.1007/s10236-003-0036-9, 2003.

Fekete, B. M., Vörösmarty, C. J., and Grabs, W.: High-resolution fields of global runoff combining observed river discharge and simulated water balances, Global Biogeochemical Cycles, 16, 15-11-15-10, https://doi.org/10.1029/1999GB001254, 2002.

Lyu, G., Wang, H., Zhu, J., Wang, D., Xie, J., and Liu, G.: Assimilating the along-track sea level anomaly into the regional ocean modeling system using the ensemble optimal interpolation, Acta Oceanologica Sinica, 33, 72-82, 10.1007/s13131-014-0469-7, 2014.