Response to Benjamin Rabe

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

Summary comment:

My name is Benjamin Rabe and I have been asked to review the manuscript "Arctic sea level variability from high-resolution model simulations and implications for the Arctic observing system" by Guokun Lyu and coauthors.

Overall, this is a very interesting paper, and the use of high-resolution ice-ocean simulations to evaluate observational coverage and variability seen in advanced analyses of both in-situ and satellite data is likely to improve knowledge in the community and enhance future analyses of Arctic sea level and freshwater content / salinity. The paper is generally well written in terms of structure and language. I see a few issues with the current version of the manuscript: there are several citations important for this topic that have not been considered, notably studies on in-situ observations. Further, there are open question as to the optimal analysis method described in the appendix. Data citations are almost entirely missing, which needs to be corrected to comply with FAIR principles.

Please consider my detailed suggestions given as comments in the "supplement" PDF. Overall, I would consider this manuscript publishable subject to the modest corrections I suggest.

Response:

We thank Dr. Benjamin Rabe for the careful reading of the manuscript, the detailed comments, and suggesting literature on in-situ observations, which helped to improve the manuscript. Indeed, there are different interpolation methods each having different assumptions. Comparative studies should be further conducted to identify their advantages and disadvantages on reconstructing the Arctic hydrographic state. A thorough discussion of that point is out of our scope. We have completed our data citation, as the reviewer suggested.

For the minor comments, we have revised the manuscript point-by-point according to the reviewer’s advice. Below we respond to the reviewer’s questions and suggestions with the key points highlighted in red.

Page 2:

Q[1] L14-16: ‘Satellite altimetric observations and Gravity Recovery and Climate Experiment (GRACE) measurements could be used to infer freshwater content changes in the Canadian Basin at periods longer than one year.’ This has been shown before, e.g. Giles et al. (2012; doi: 10.1038/ngeo1379) and Morison et al. (2012; doi: 10.1038/nature10705).

Response:

We thank the reviewer for the comment. Indeed, Giles et al. (2012) and Morison et al. (2012) proposed to infer total freshwater content in the Canadian Basin using an idealized model with satellite altimetric observations and Gravity Recovery and Climate Experiment (GRACE) measurements. Proshutinsky et al. (2019) tried to reveal the seasonal freshwater content changes in the Beaufort Gyre with this method. However, these methods are based on some assumptions and it is not clear until which timescales the assumptions hold. Therefore, our study examined those idealized methods and their limitations depending on timescales. We confirm that satellite altimetric observations and Gravity Recovery and Climate Experiment (GRACE) measurements could be used to infer freshwater content changes in the Canadian Basin at periods longer than one year. However, the method does not apply at timescales shorter than the seasonal cycle. We are not trying to state that we find the results false, but to state that these idealized methods apply at timescales longer than the seasonal cycle and fail at shorter timescales. We revised the words to "The study confirms that satellite altimetric observations and Gravity Recovery and Climate Experiment (GRACE) could infer the total freshwater content changes in the Canadian Basin at periods longer than one year, but they are unable to depict the seasonal and subseasonal freshwater content changes." (L14-L17 in manuscript).

Page 3:

Q[1] L54-55,' We further discuss the existing Arctic Ocean observing system's capability to monitor the Arctic freshwater content variability.'

Here you could cite Solomon et al. (2021; doi: 10.5194/os-17-1081-2021) and summarise briefly. If you discuss freshwater variability estimates for the Arctic, it would be worth mentioning and briefly relating to the following publications:

Haine et al. (2015, doi: 10.1016/j.gloplacha.2014.11.013)

Rabe et al. (2011, doi: 10.1016/j.dsr.2010.12.002 ; 2014, doi: 10.1002/2013GL058121)

Polyakov et al. (2020 , doi: 10.3389/fmars.2020.00491).

These use various kinds of interpolated products, based on in-situ profiles, to estimate freshwater content variability.

Response:

We thank the reviewer for suggesting the above studies. We have included the above studies in L55-61 "Altimetric and GRACE measurements, in situ hydrographic observations mapped with different interpolation schemes (e.g., Haine et al., 2015;Polyakov et al., 2008;Rabe et al., 2014;Rabe et al., 2011), and ocean reanalyses have been used to infer the basin-scale freshwater changes during the unpreceding freshwater changes since 2000s. However, Solomon et al. (2021) pointed out that large uncertainties and discrepancies remain in revealing the regional patterns. In this study, we further discuss the existing Arctic observing system's capability to monitor the Arctic freshwater content variability and identify observational gaps in time and space."

Page 4:

Q[1]: I see in line 123 you mention that this does not imply a volume flux but only a salinity restoring. Please briefly explain in the discussion why it does not matter for this sea level study.

Response:
We thank the reviewer's suggestion. Using the virtual salt flux parameterization fails to mimic impacts of volume input on sea level variability. This could be problematic especially in the river mouths and their surrounding areas (Proshutinsky et al., 2007). We discuss the potential impacts of virtual salt flux on the seasonal cycle in the conclusion and discussion parts (L454-456, L458-461).

Q[2]: Is there a reason why you used WOA and not PHC, which is the "classical" climatology for the Arctic, using otherwise unavailable (Russian) observations, that are not included in WOA?

Response:
There is no specific reason for using WOA, rather than PHC. Indeed, PHC is a better pre-2000 Arctic climatology than WOA due to the Russian observations. However, these ATLARC models are set up for both Arctic and Atlantic studies. They are used to explore ocean dynamics in the tropics, subtropics and pan-Arctic regions. Because we are familiar with WOA data, of its good quality and updated frequently, we choose the WOA datasets in the simulation.

Q[3]. This section lacks data citations (note: just citing the scientific analysis papers where data are used is not according to FAIR principles): all the data should be available in repositories with a full citation (incl. doi). Please add those to the text and to your reference list. As an example, for ITP data, use Toole et al. (2016, doi: 10.7289/v5mw2f7x); see also https://www2.whoi.edu/site/itp/data/data-products/ .

Response:
Thanks for pointing out the incomplete data citation. As the reviewer suggested, we have included the data DOI and URL for assessing the repositories of GRACE and altimetric data, the Beaufort Gyre Exploration Project data, and the North Pole Environmental Observatory data in Line 97-104. Also, data sources are listed in "Section 7. Data Availability".

Page 7
Q[1] I suggest to make the letters a-f white -- easier to see against the gray land mask. Alternatively, highlight the letters with a white disc in the background. It would be easier to understand this figure at a glance by putting row and column labels adjacent to the figures (e.g. at top and to left).

Response:
We thank the reviewer's suggestion for improving the figures. We have redrawn the figures, using outside labels at the left top.

Q[2] I think this whole paragraph deserves a bit more detail: what about the effect of model resolution and (not) resolving mesoscale eddies? Those play a significant role in the dynamics of the Beaufort Gyre, for example (e.g. Armitage et al., 2020; doi: 10.1038/s41467-020-14449-z ; and references therein). How does the altimetry product SSH perform close to the coast?

Response:
We thank the reviewer's advice. We have rewritten L154-169, including the discussion of potential impacts of resolving transient eddies. The altimetric data has higher errors and lower correlation with tide gauges in the ice-covered Arctic marginal seas (Armitage et al., 2016). However, altimetric data is the only SLA dataset that covers the vast Arctic Ocean and reveals the basin-scale SLA variability pattern. We take it as a reference to check how the model simulations, which usually underestimate SLA variability, reproduce the basin-scale SLA variability.

Page 9: This caption is lacking a clear mention of what model output is used (you mention it somehow at the end of section 3., but would really help to have that here, as well).
The letters a-f are easier to see here, as the gray background is lighter than in Figure 3. However, I'd still think outside labels for rows / columns would speed up understanding this figure.

Response:
We thank the reviewer's advice. We added "The high-frequency and seasonal variability (a, b, d, and e) uses the daily output of ATLARC04km, and decadal variability (c and f) uses the monthly output from ATLARC08km." to the caption to clarify. Moreover, we revised the figure, putting the labels outside of the panels.

Page 10: the blue boxes and the letters "A" and "B" are difficult to see -- perhaps put letters in bold font and white?

Response:
Thanks for the suggestion. We have reproduced Fig. 5 with the boxes and letters enlarged.

Page 11:
Q[1] The depiction of the phase by vectors is a bit confusing to the non-expert- perhaps remove vectors and add another panel with phase contours/color?

Response:
We thank the reviewer's suggestion. We separate the amplitude and phase of the transfer function in two panels (Fig. 5a and b) in the revised manuscript.

Q[2]. Worth mentioning somewhere in the paper if correlation coefficients are significant at some level (e.g. 1 or 5 %).

Response:
We added "Correlation coefficients with 95% significance level are plotted." in Fig. 6 caption (L241). Also, we reproduced Fig. 6 and left blank where correlation coefficients are not significant (95% significance level).

Q[3] Are those correlation coefficients significant?

Response:
We thank the reviewer's comment. We checked the correlation coefficients and the significance levels and noted that not all is significant. We filtered out correlation coefficients that are not significant (95% significance level) in Fig. 6.

Q[4] Need to show lines where correlation coefficients are significant, unless they are significant everywhere. In the latter case, this deserves at least one sentence.

Response:
We take the reviewer's comment and filter out correlation coefficients that are not significant (95% significance level). Also, we added one sentence in Fig. 6 caption to clarify that only significant correlation coefficients are shown.

Q[5] The unit vector could be more prominently places at the top left of each figure (gets a bit lost in Greenland, reaching into the EGC).

Response:
We thank the reviewer's suggestion. We have reproduced Fig. 6, moving unit vectors and letters to the top left of each panel.

[6] The caption is a bit confusing as to what is c -- perhaps clarify by separating into two sentences? (you write it in the text, but should be clear in the caption)

Response:
We thank the reviewer's suggestion. We have clarified panels (b) and (c) separately in Fig. 6 caption.

[7] Do I understand correctly, that (a) is the correlation of local wind to local sea level, whereas (b) and (c) denote the correlation of each local wind across the Arctic to the averages of the boxes A and B in Figure 5a?

Response:
Exactly. Panel (a) is the correlation of local SLA to local wind stress (vectors) and stress curl (shading), which explore the relation of SLA to wind stress and the curl

(Ekman transport and pumping). Panels (b) and (c) are two showcases to further illustrate propagation features in the SLA signal. To make our idea clear, we rephrase L220-234 and remade Fig. 6 and its caption.

Page 14

[1] Here I would see it appropriate to also cite the estimates based on in-situ observations, covering the whole of the Arctic basin -- Rabe et al. (2011; 2014), Haine et al. (2015) and Polyakov et al. (2020) -- see my prior comment for doi.

Response:

We thank the reviewer for suggesting the related studies. We have added the respective citations (L304-306).

Page 15

Q[1] "The model simulation indicates" (btw.: which one -- the 4 km ?)

Response:

We rely on the ATLARC08km (8km) to explore the decadal variability since ATLARC04km (4km) only covers the periods 2003-2012. We changed the sentence to “The ATLARC08km simulation revealed” to clarify.

Q[2] Please details, with reference to literature, what happened in the GIN seas during the time covered by the model run (e.g. Somavilla et al., 2013, doi: 10.1002/grl.50775 ; Ronski and Budeus, 20015, doi: 10.1029/2004JC002318).

Response:

We thank the reviewer’s comment. “The thermosteric effect dominates in the GIN seas, mainly relating to the convection processes (Brakstad et al., 2019;Ronski and Budéus, 2005). Brakstad et al. (2019, see their Fig. A1) demonstrated that a change from shallow convection to deep convection can lead to temperature changes of more than -0.2 °C over the upper 600 m and salinity changes of 0.02 PSU over the upper 200 m, resulting in a significant thermosteric effect.” We added the above words to explain that convection changes result in the significant thermosteric effect (L 310-314).

Q[3] “in this region”

Response:

We revised the related sentence (L315).

Q[4] Is that trend significant? Difficult to see in Figr. 10 d...

Response:

The linear trend of the thermosteric effect is significant (green lines Figure R1 d and e), compensated by trends of halosteric effect. It is not clear whether this is true signal or just because of model spin up. In our study, we mainly concentrate on the variability and removed the trend in Fig. 10. We added "Linear trends in all the timeseries are removed in panels (d) and (e) " to Fig. 10 caption.

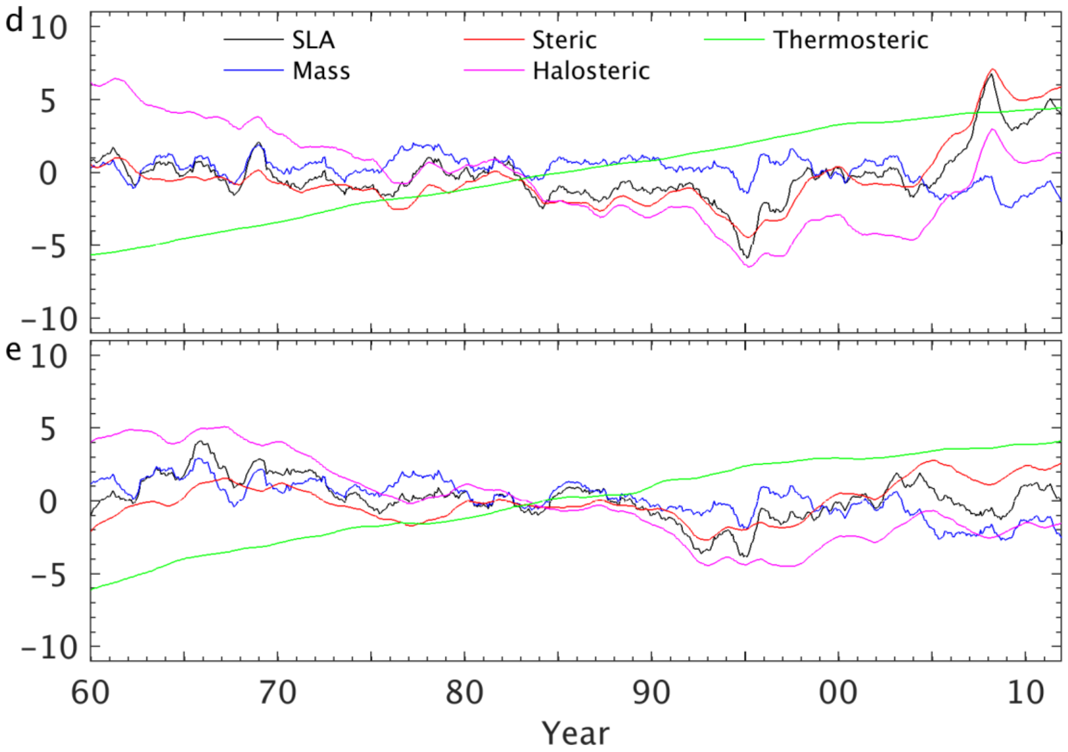

Figure R1. Time series of sea level anomaly and mass, steric, and thermo/halosteric components in the (d) Canadian and (e) Eurasian basins (see the regions in Fig.10 b and e), respectively.

Q[5] Why "likely related to..." ? Please explain how this is indicated in the model results and/or cite literature...

Response:
We thank the reviewer's comment. The interannual to decadal mass variability pattern resembles the barotropic response of sea level to the barotropic response of Arctic circulation to the changes in the Icelandic low and the Arctic Oscillation (Proshutinsky and Johnson, 1997). For the reviewer's information, we show correlation coefficients of mass changes in the Eurasian Basin to mass component anomalies (shading Fig. R2) and wind stress anomalies in the pan-Arctic Ocean (vectors in Fig. R2). A weaker Iceland low leads to anticyclonic wind stress anomalies in the GIN seas, resulting in more mass transport to the GIN seas. At the same time, the anticyclonic wind stress anomalies (high-index AO) in the Arctic Ocean result in high SLA in the central Arctic and low SLA in the Arctic marginal shelves, especially in the East Siberian Sea.

We added, "In addition, the mass components contribute to the interannual sea level variability (blue lines in Fig. 10d and e) in both the basins. We note that the mass changes are highly correlated in the Canadian and Eurasian basins (r>0.98 with 95% significance level). They are positive correlated to the mass changes in the deep basin of the GIN seas and the Arctic Ocean and are negative correlated to mass changes in the Arctic marginal shelves, especially in the East Siberian Sea, representing a barotropic response of sea level to changes of the intensity and locations of the Icelandic low and the East Siberian high (e.g., Proshutinsky and Johnson, 1997)." (L320-325) to explain these barotropic signals.

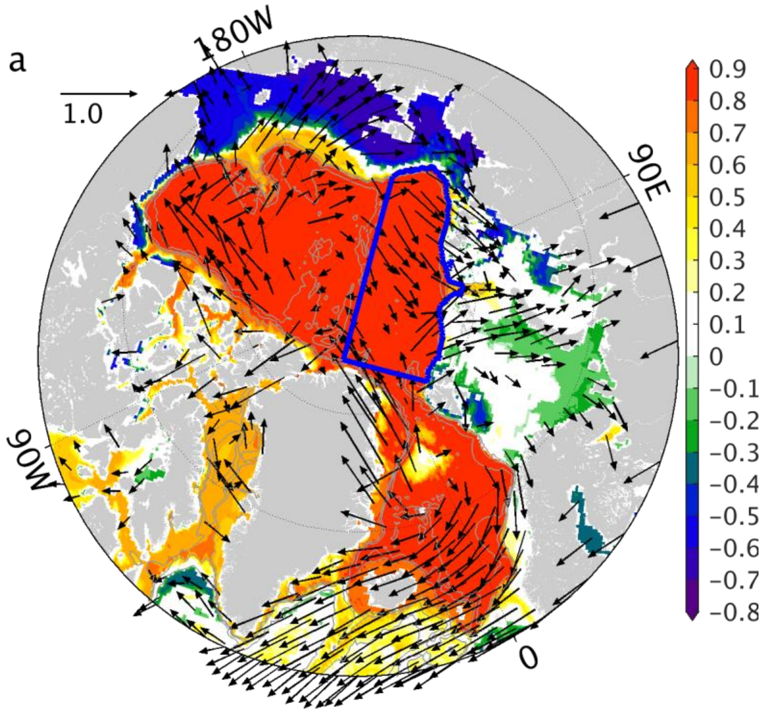

Figure R2. Coefficients of the correlation between the mass component averaged in the Eurasian Basin (enclosed by the blue line) and the mass variation (shading) and wind stress (vectors).

Page 16

Q[1] Regional boxes not clearly labelled -- please mark the "d" and "e" in Fig. 10 b clearly.

Response:

We thank the reviewer's suggestion and we have labelled regions with "d" and "e" in Fig. 10b.

Q[2] Define freshwater content and fresh water concentration (see e.g. Aagard and Carmack, 1989, doi: 10.1029/JC094iC10p14485). Please also see the discussion in Solomon et al. (2021,doi: 10.5194/os-17-1081-2021), Forryan et al. (2019, doi: 10.5194/tc-13-2111-2019) and Schauer and Losch (2019, doi: 10.1175/JPO-D-19-0102.1) regarding the use of fresh water in the (Arctic) ocean.

Response:

We thank the reviewer for pointing out the definition of freshwater content, freshwater inventory and "freshwater fraction" and suggesting the related studies on the Arctic freshwater changes. Throughout our study, we use "freshwater fraction" to get a fair comparison with previous studies. We defined them as "Freshwater inventory is defined, as in Rabe et al. (2011) and Schauer and Losch (2019), the freshwater fractions relative to a conventional reference salinity S_0 =34.8 PSU integrated over depth, and freshwater content is the total freshwater inventory over a region:

$$FWC = \int FWI\, dA = \int \int_H^0 \frac{S_0 - S}{S_0} dz\, dA \quad (5),$$

with H being the depth of the 34.8 isohaline. The reference salinity indicates the mean salinity within the Arctic Ocean and can differ slightly in previous studies, which mainly impacts on the mean state of freshwater content. " (L340-346)

Q[3] The method of correcting ITP profilers (WHOI) for drift in the conductivity sensor is analogous to the method used for ARGO floats. "Historical" reference profiles are used in an optimal interpolation approach to compare to in-situ profiles in a certain depth range. For that reason it's not useful to consider the deeper part of the profile (deeper than about 500 m) to analyse long-term variability/trends, as they would likely not show up. The analysis by Rabe et al. (2011; 2014) and others thus only considered observational data shallower than 500 m, or even limited the analysis to the layer shallower than the lower halocline (practical salinity < 34). Due to this fact, Sumata et al. (2018, doi: 10.5194/os-14-161-2018) used only observational data in the top 400 m in their analysis of Arctic Ocean decorrelation scales. See also https://www2.whoi.edu/site/itp/wp-content/uploads/sites/92/2019/08/ITP_Data_Processing_Procedures_35803-1.pdf for ITP processing procedure (section IV.D.).

Response:

We thank the reviewer for providing information about ITP processing procedures and explaining reasons why previous studies only considered observational data shallower than 500 m. We limit the depth to 800 m just because the ITP could reach ~760 m and the nearest model level is 800 m.

In the model simulations, the 34.8 PSU halocline is usually smaller than 450 m (see Fig. 12c and d for an example). Therefore, data below this layer is actually not used in computing freshwater content and use of the criteria of 500 m should not change our conclusions in this study. Besides, improvement of error correction techniques may probably make the data below 500 m useful in the future.

Q[4] Very nice discussion! First time I really see anyone comparing the approaches by each Giles and Morison.

Response:
We thank the reviewer's appreciation of this section.

Q[5] Please use a couple of sentences to discuss the potential error by assuming a standard density profile or estimating this constant in the SSH-based estimate of freshwater content.

Response:
We thank the reviewer's comment. Parameter α is a constant value estimated from in-situ profile observations and is set to 35.6. Uncertainties of α just result in an offset to the freshwater content time series using Eq. (7). We added, "The choice of α just contributes a static offset to freshwater content estimation in Eq. (7)." (L359) to discuss the impacts of α on freshwater content estimation.

Q[6] What area did you consider -- e.g. "Arctic" bounded by what?

Response:
We thank the reviewer for pointing out this problem. Here, we considered the Canadian Basin which is similar as in Giles et al. (2012) and Morison et al. (2012). We added a subplot in Fig. 11a to show the regions that we considered.

Page 17
Q[1] It would be useful here to have a panel with the difference between the red and black lines (referred to in the text, "long term trend").

Response:
We thank the reviewer's suggestion and have added another panel (Fig. 11b) to display the difference between the annual mean freshwater content changes to the estimated values using the methods of Morison et al. (2012) and Giles et al. (2012).

Q[2] "model" (again, is that the 4 km one?)

Response:
Here, we use the monthly output of the ATLARC08km. We added "using the monthly output of ATLARC08km" in Fig. 11 caption.

Q[3] "were" and [4] "did"

Response:
We thank the reviewer for pointing out the mistakes. We have corrected the mistakes in the revised version.

Page 18

Q[1] Please define "difference" -- is it the latter period MINUS the former, or vice versa? (b) suggests that it's 2008-2010 MINUS 1994-1996 (i.e. FW content increase).

Response:
The differences should be Feb. 2003 minus Sep. 2002, and 2008-2010 minus 1994-1996. To clarify the definition of "difference", we revised Fig. 12 caption as "The differences of freshwater content (shading), sea level anomaly (0.15 m contour, black lines), and wind stress (vectors) from (a) Feb. 2003 to Sep. 2002, and (b) 2008-2010 to 1994-1996."

Q[2] Units are missing on the colorbars!

Response:
We thank the reviewer for pointing out the missing unit on all the colorbars. We have reproduced all figures in the manuscript with units.

Q[3] What you are plotting in colour are the FW inventories (presumeable in "m"), not the content (that being a volume quantity, i.e. "m^3").

Response:
Figs. 12a and b show differences of freshwater inventories in meters. To clarify, we have reproduced Fig. 12, added units on the colorbar, and stated in the caption "The differences of freshwater inventory in meters (shading)".

Q[4] This is a nice study making use of the model runs presented here.
However, this section deserves reference to existing works. For example, Rabe et al. (2014, doi:10.1002/2013GL058121) do not resolve the seasonal cycle, using data from 1992 to 2012, but instead use a 6-year moving window to weigh data in time and space using an optimal interpolation method. The final interpolated product showed high error for the annual mean estimate of Arctic Basin freshwater content, indicating that shorter than interannual / multi-year variability is not adequately resolved by those observations. IT's at least worth a paragraph of discussion.
Again, much work has been done, e.g. by Rabe..., Polyakov... and also Haine... -- please cite appropriately here and/or above (see prior comments).

Response:
We appreciate the reviewer's comments and advice. We added "Using historical hydrographic observations and different objective mapping techniques, previous studies (e.g., Haine et al., 2015;Polyakov et al., 2008;Rabe et al., 2014;Rabe et al., 2011) have explored Arctic freshwater content changes and mechanisms on multi-year periods. However, the interpolated products suffers from high uncertainties at timescales shorter than multi-year periods (e.g., Fig. 4 in the supplement of Rabe et al., 2014), indicating observational gaps on resolving the seasonal to interannual freshwater content changes. Besides, observational gaps depending on geographic

locations are observed (e.g., Fig. 7 in Rabe et al., 2011) but not explored yet." (L404-410) to introduce studies using hydrographic observations and complement this section.

Page 19

Q[1] "inventory"

Response: We thank the reviewer's comment and have changed "content" to "inventory" here.

Q[2] The regional selection is somewhat arbitrary -- best use either the topographic basin boundaries (e.g. denoted by continental slope isobath and Alpha-Mendeleyev Ridge). The Beaufort Gyre follows dynamics that may show variability in this box that is not related to FW content changes in the whole gyre.

Response:

We thank the reviewer's suggestion. We redefined the region depending on topography: from the southern periphery of the Beaufort Gyre to the Alpha-Mendeleyev Ridge (Fig .13).

Q[3] lack

Response: We thank the reviewer for pointing out this mistake and we have revised it in the revised manuscript.

Page 20

Q[1] Here we have a mixture of: 1) regional observation density in time and space; 2) variance of regional observations. Due to 1) we would expect high errors on the shelves, whereas due to 2) we see errors in the well-sampled Canada Basin. Please discuss in a couple of sentences.

Response:

We thank the reviewer's comment. It is straightforward that a low density of observations results in high errors, including the marginal seas and the deep basin before 2007, as suggested by the comment 1). However, we are not sure what "2) variance of regional observations" means.

The ensemble optimal interpolation method in this study is as following:

$$\varphi_g^a = \varphi_g^b + \frac{\varphi'_g \varphi_g'^T H^T}{H\varphi'_g \varphi_g'^T H^T + \gamma\gamma^T}(d - H\varphi_g^b) \cdot e^{-\frac{x^2}{2\sigma^2}},$$

where the analysis field at a grid (φ_g^a) is a linear combination of a background value at a grid (φ_g^b, mean over 1992-2012 in this study) and the model-data misfits ($d - H\varphi_g^b$) weighted by the ratios of background covariances and observation covariances

$(\frac{\varphi'_g \varphi'^T_g H^T}{H\varphi'_g \varphi'^T_g H^T + \gamma\gamma^T})$ and a decorrelation scale function ($e^{-\frac{x^2}{2\sigma^2}}$). In this formulation, the salinity increment (the second term on the right hand side) depends on the model-data misfit ($d - H\varphi^b_g$), choice of the decorrelation distance (σ), representation errors of the observations (γ), covariance of background state at the observational locations ($H\varphi'_g \varphi'^T_g H^T$) and between the target grid point and observational locations ($\varphi'_g \varphi'^T_g H^T$).

We assume that the reviewer indicates the representation errors (γ) with " 2) variance of regional observations", as used in Rabe et al. (2011). In this study, we use fixed profiles of representation errors from 0.09 PSU at the surface to 0.03 PSU at the bottom. Therefore, the residual errors only indicate the observational gaps due to observational density in time and space.

To make our conclusion clear, we revised Fig. 14 and added "We further examined RMS errors of freshwater inventory from 1992-2006 (Fig. 14a), 2007-2012 (Fig. 14b), and the corresponding locations of profiles (Fig. 14c and d). The lack of in-situ profiles in the Arctic shelves (Fig. 14) and in the deep basin from 1992-2006 (Fig. 14 a and c) results in pronounced errors. The ITP profiles (trajectories in Fig. 14d) enhanced the capability of observing the Arctic freshwater changes in the deep basin and the winter season, reducing freshwater inventory uncertainties significantly (Fig. 14b). Additionally, significant errors remain in regions with high variability (e.g., EGC/WGC), in the Laptev Sea and the Alaskan coast which also extend from the coasts to the deep basin, underlining the observing requirements." (L422-428) to the manuscript.

Q[2] this discussion ignores all the estimates of FW content based on in-situ observations. Please include this in your discussion, as you specifically look at the use of those observations in your analysis. (see my prior comments for references)

Response:
We thank the reviewer's comment. We discussed the studies of in-situ profiles in L474-478 "Previous studies have applied different objective mapping methods (Haine et al., 2015;Polyakov et al., 2008;Rabe et al., 2014;Rabe et al., 2011) to reconstruct the Arctic freshwater content changes and budget. However, the interpolated product still show high errors for the annual mean estimate of freshwater content, indicating potential observational gaps on resolving the seasonal cycle of freshwater content. We further examined the observational gaps in time and space using monthly output from ATLARC08km." to complement the conclusions.

Page 21
Q[1] which? all isopycnals (i.e. stratification)?

Response: Here we mean the upper layer indicated by the 27.9 kg m^{-3} isopycnal. We revised " isopycnal" to " the upper layer (indicated by the 27.9 kg m^{-3} isopycnal in this study)" (L465-466).

Q[2] "Cautions" should be "Caution"

Response: We thank the reviewer for pointing out the typo and we have corrected it.

Q[3] Consider citing Lee et al. (2019, doi: 10.3389/fmars.2019.00451).

Response:

We thank the reviewer for suggesting the literature on the development of Arctic observing system. We have incorporated the related literature into the discussion "Further observing system simulation experiments (e.g., Lyu et al., 2021;Nguyen et al., 2020) should be performed in a coordinated fashion to develop an autonomous Arctic observing system (Lee et al., 2019;Sandu et al., 2012) to meet the societal and scientific needs ." (L484-L485).

Q[4] "coordinately" should be "in a coordinated fashion".

Response: We thank the reviewer's comment and have revised this in the manuscript.

Q[5] See my prior comment -- you need data citations!!!

Response:

We thank the reviewer's comment about the data citation problem. We have added citations, including their URL, in the "Section 7 data available". "The Beaufort Gyre Exploration Program data were collected and made available by the Woods Hole Oceanographic Institution (https://www2.whoi.edu/site/beaufortgyre/) in collaboration with researchers from Fisheries and Oceans Canada at the Institute of Ocean Sciences and were derived from https://www2.whoi.edu/site/beaufortgyre/data/mooring-data/. The North Pole Environmental Observatory data were derived from http://psc.apl.washington.edu/northpole/Mooring.html. The satellite altimetric and GRACE measurements were retrieved via http://www.cpom.ucl.ac.uk/dynamic_topography and https://podaac.jpl.nasa.gov/announcements/2021-06-11-GRACE-and-GRACE-FO-L3-Monthly-Ocean-and-Land-Mass-Anomaly-RL06-04-Dataset-Release. We gratefully acknowledge the Ice- Profiler Program based at the Woods Hole Oceanographic Institution (https://www.whoi.edu/itp) and the Unified Database for Arctic and Subarctic Hydrography (https://doi.pangaea.de/10.1594/PANGAEA.872931) collected and compiled by the Alfred Wegener Institute."

Page 22

Q[1] then you might as well acknowledge the WHOI ITP program (see their website -- my prior comment).

Response:
We appreciate the reviewer's comment and we now acknowledge the WHOI-ITP program and reference.

Q[2] Mean at each grid point or mean over the whole domain and time period? (i.e. not a field, but a single scalar)

Response:

Here, the "mean" indicates mean at each grid over the period 1992-2012. We revised the words and equation to "At one grid (denoted by subscript g), the analysis state φ_g^a is a linear combination of a background field φ_g^b and surrounding in-situ observations d:

$$\varphi_g^a = \varphi_g^b + K(d - H\varphi_g^b) \cdot e^{-\frac{x^2}{2\sigma^2}} \quad \text{(A1),"}$$

and also added "the background state of salinity φ_g^b is taken as the mean salinity at each grid over the period 1992-2012" to clarify it.

Q[3] What is that based on? The instrument error does not depend on depth! ... but the spatial representativeness of the data for a whole grid box likely does, due to decorrelation scales (see my earlier comment / citatation of Sumata et al.).

Response:
We thank the reviewer for pointing out this mistake. Here, we mean the representation errors, rather than the instrumental errors. We have revised this terminology (L529) in the revised manuscript.

Q[4] Please state the function -- e^(x/scaling) or similar...(?)

Response:
We thank the reviewer's suggestion and have added the Gaussian function explicitly in Eq. A1:

$$\varphi_g^a = \varphi_g^b + K(d - H\varphi_g^b) \cdot e^{-\frac{x^2}{2\sigma^2}} \quad \text{(A1),}$$

and explain the function as "Therefore, we introduce a Gaussian function depending on the distance between observational locations and the model grid (x in Eq. A1) and an decorrelation radius (σ in Eq. A1) to ensure ...."

Q[5] Do you consider the water depth (e.g. planetary potential vorticity) or if not, please comment why that does not matter (see also Rabe et al., 2011, 2014; doi see prior comment). What is your time scale (or is there any in the Gaussian)? Do you consider all data or do you have a moving time selection window?

Response:
In this study, we only considered the horizontal correlations and didn't consider the vertical and temporal correlations. Therefore, at a target month and grid, we only use the observations at the same month/year and the same layer (depth) to compute salinity. Potentially, both vertical and temporal correlations can be used to derive a more accurate interpolated product (e.g., Rabe et al., 2011) since could help to distribute observed information to regions that are not observed. However, introducing vertical and temporal correlations introduces more parameters (e.g., length of decorrelation radius) that must be decided when using "real" data.

For any interpolation method, data at one grid and time depends more on nearby observations and less on far away observations (both time and space). Since we have more knowledge on the horizontal correlation scales and less on the vertical and time, and assume the profiles extend to the top 800 m, we only use the horizontal correlation in this study. Some observational information may not be fully extracted without considering the temporal and vertical correlations, but the simplifications still help to depict the observational gaps in time and space clearly.

For observational datasets, we generate the synthesis data based on the compiled data set of "Unified Database for Arctic and Subarctic Hydrography" (Behrendt et al., 2018), which collects a wide range of profiles. The synthesis data is generated based on the temporal and spatial distribution of UDASH and no moving time window is used to select data.

Page 23:
Q[1] only for 2008, annual average of monthly fields?

Response:
The background state is the mean salinity at each grid point over 1992-2012. We use salinity state from August 1992 and observation locations from the entire year of 2008. This is only a test case to decide an approximated horizontal decorrelation length and show how this method works. The decorrelation length should not change in principle too much if we choose another year.

Q[2] this may be biased -- in 2007 the central and Eurasian Arctic was much better covered by obs., whereas in 2008 the region north of the East Siberian Sea was.

Response:

We thank the reviewer's comment. Again, this is only a show case to decide an approximate horizontal decorrelation length which may vary slightly. Comparative studies are required to test different interpolation methods and the decorrelation length based on "physical processes" (Proshutinsky et al., 2009;Rabe et al., 2011) and statistic correlation based on model simulations or reanalyses (such as this study), making full use of existing observations.

References:

Armitage, T. W., Bacon, S., Ridout, A. L., Thomas, S. F., Aksenov, Y., and Wingham, D. J.: Arctic sea surface height variability and change from satellite radar altimetry and grace, 2003–2014, Journal of Geophysical Research: Oceans, 121, 4303-4322, 10.1002/2015JC011579, 2016.

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.

Brakstad, A., Våge, K., Håvik, L., and Moore, G. W. K.: Water mass transformation in the greenland sea during the period 1986–2016, Journal of Physical Oceanography, 49, 121-140, 10.1175/jpo-d-17-0273.1, 2019.

Giles, K. A., Laxon, S. W., Ridout, A. L., Wingham, D. J., and Bacon, S.: Western arctic ocean freshwater storage increased by wind-driven spin-up of the beaufort gyre, Nature Geoscience, 5, 194, 10.1038/ngeo1379, 2012.

Haine, T. W. N., Curry, B., Gerdes, R., Hansen, E., Karcher, M., Lee, C., Rudels, B., Spreen, G., de Steur, L., Stewart, K. D., and Woodgate, R.: Arctic freshwater export: Status, mechanisms, and prospects, Global and Planetary Change, 125, 13-35, https://doi.org/10.1016/j.gloplacha.2014.11.013, 2015.

Lee, C. M., Starkweather, S., Eicken, H., Timmermans, M.-L., Wilkinson, J., Sandven, S., Dukhovskoy, D., Gerland, S., Grebmeier, J., Intrieri, J. M., Kang, S.-H., McCammon, M., Nguyen, A. T., Polyakov, I., Rabe, B., Sagen, H., Seeyave, S., Volkov, D., Beszczynska-Möller, A., Chafik, L., Dzieciuch, M., Goni, G., Hamre, T., King, A. L., Olsen, A., Raj, R. P., Rossby, T., Skagseth, Ø., Søiland, H., and Sørensen, K.: A framework for the development, design and implementation of a sustained arctic ocean observing system, Frontiers in Marine Science, 6, 10.3389/fmars.2019.00451, 2019.

Lyu, G., Koehl, A., Serra, N., and Stammer, D.: Assessing the current and future arctic ocean observing system with observing system simulating experiments, Quarterly Journal of the Royal Meteorological Society, n/a, 1-21, 10.1002/qj.4044, 2021.

Morison, J., Kwok, R., Peralta-Ferriz, C., Alkire, M., Rigor, I., Andersen, R., and Steele, M.: Changing arctic ocean freshwater pathways, Nature, 481, 66, 10.1038/nature10705, 2012.

Nguyen, A. T., Heimbach, P., Garg, V. V., Ocaña, V., Lee, C., and Rainville, L.: Impact of synthetic arctic argo-type floats in a coupled ocean–sea ice state estimation framework, Journal of Atmospheric and Oceanic Technology, 37, 1477-1495, 10.1175/jtech-d-19-0159.1, 2020.

Polyakov, I. V., Alexeev, V. A., Belchansky, G. I., Dmitrenko, I. A., Ivanov, V. V., Kirillov, S. A., Korablev, A. A., Steele, M., Timokhov, L. A., and Yashayaev, I.: Arctic ocean freshwater changes over the past 100 years and their causes, Journal of Climate, 21, 364-384, 10.1175/2007jcli1748.1, 2008.

Proshutinsky, A., Ashik, I., Häkkinen, S., Hunke, E., Krishfield, R., Maltrud, M., Maslowski, W., and Zhang, J.: Sea level variability in the arctic ocean from aomip models, J Geophys Res-Oceans, 112, 10.1029/2006jc003916, 2007.
Proshutinsky, A., Krishfield, R., Timmermans, M.-L., Toole, J., Carmack, E., McLaughlin, F., Williams, W. J., Zimmermann, S., Itoh, M., and Shimada, K.: Beaufort gyre freshwater reservoir: State and variability from observations, Journal of Geophysical Research: Oceans, 114, 10.1029/2008jc005104, 2009.

Proshutinsky, A. Y., and Johnson, M. A.: Two circulation regimes of the wind-driven arctic ocean, Journal of Geophysical Research: Oceans, 102, 12493-12514, 10.1029/97JC00738, 1997.
Rabe, B., Karcher, M., Schauer, U., Toole, J. M., Krishfield, R. A., Pisarev, S., Kauker, F., Gerdes, R., and Kikuchi, T.: An assessment of arctic ocean freshwater content changes from the 1990s to the 2006–2008 period, Deep Sea Research Part I: Oceanographic Research Papers, 58, 173-185, https://doi.org/10.1016/j.dsr.2010.12.002, 2011.
Rabe, B., Karcher, M., Kauker, F., Schauer, U., Toole, J. M., Krishfield, R. A., Pisarev, S., Kikuchi, T., and Su, J.: Arctic ocean basin liquid freshwater storage trend 1992–2012, Geophysical Research Letters, 41, 961-968, https://doi.org/10.1002/2013GL058121, 2014.
Ronski, S., and Budéus, G.: Time series of winter convection in the greenland sea, Journal of Geophysical Research: Oceans, 110, https://doi.org/10.1029/2004JC002318, 2005.
Sandu, I., Massonnet, F., van Achter, G., Acosta Navarro, J. C., Arduini, G., Bauer, P., Blockley, E., Bormann, N., Chevallier, M., Day, J., Dahoui, M., Fichefet, T., Flocco, D., Jung, T., Hawkins, E., Laroche, S., Lawrence, H., Kristianssen, J., Moreno-Chamarro, E., Ortega, P., Poan, E., Ponsoni, L., and Randriamampianina, R.: The potential of numerical prediction systems to support the design of arctic observing systems: Insights from the applicate and yopp projects, Quarterly Journal of the Royal Meteorological Society, n/a, https://doi.org/10.1002/qj.4182, 2012.
Schauer, U., and Losch, M.: “Freshwater” in the ocean is not a useful parameter in climate research, Journal of Physical Oceanography, 49, 2309-2321, 10.1175/jpo-d-19-0102.1, 2019.
Solomon, A., Heuzé, C., Rabe, B., Bacon, S., Bertino, L., Heimbach, P., Inoue, J., Iovino, D., Mottram, R., Zhang, X., Aksenov, Y., McAdam, R., Nguyen, A., Raj, R. P., and Tang, H.: Freshwater in the arctic ocean 2010–2019, Ocean Sci., 17, 1081-1102, 10.5194/os-17-1081-2021, 2021.