Response to Reviewer 1

We are grateful for your insightful comments on our manuscript and have revised the manuscript accordingly. All your comments (in blue) are addressed (in black) point by point, with new text added in the manuscript highlighted in *Italic*.

This article presents a new NEMO based configuration for the Bohai Sea, which is a small semi-enclosed and very shallow area in North Eastern China, located at the latitude of Beijing. It is to my knowledge the smallest area covered by a NEMO configuration. The authors particularly focus on the sea-ice characteristics of the area.

The concept is interesting, Beijing is located at a low latitude (Valencia in Spain, in European standards) where the presence of sea-ice is possible only due to a combination of cold continental winters, very shallow waters and low salinity in the Bohai Sea. This makes the Bohai Sea very sensitive to climate change from the atmosphere but also from the ocean point of view.

From a general perspective, I think the article in its present state does not explore such aspects thoroughly enough, which is a bit sad because I believe this aspect to be really interesting. Therefore I think this article could be published in GMD after major revision.

We greatly appreciate the reviewer for the interest in our work. We have revised the manuscript in this regard to tell a more comprehensive story about Bohai Sea ice. In particular, the ocean part has now been added into the discussion covering aspects related to the temperature and salinity stratification, currents, and water volume exchanges with the Yellow Sea, and etc., in addition to sea ice itself.

Also there are editing problems in pages 6-10 of the article, the authors made an online comment on this but only for an array, which does not improve the readability at all. I strongly advise to correct this to make the work of reviewers nicer to do.

Thank you for your comment. We recognize that the garbled items are due to technical issues that affect the readability and have been corrected in this revised version.

Most important comments:
- First, could you present the Bohai Sea a bit better. Especially we would like to understand what makes there is sea ice in the Bohai Sea. Basically there would not be any sea ice in the deep ocean at such a latitude. Is there sea ice in the Bohai Sea because it is very shallow or because of the low salinity or both? Basically, please provide a good hydrography of the Bohai Sea.

Yes, understanding the formation of sea ice in the Bohai Sea is a subject of great concern. Following your suggestions, we have detailed this part in the introduction:

The formation of sea ice in the Bohai Sea mainly depends on the geographical environment and hydrometeorological characteristics (Ding, 1999). Specifically, the Bohai Sea is located in the continental shelf area, and the average water depth is only 18 m (Su and Wang, 2012), which indicates low oceanic heat content in winter. Following a northern continental climate, the Bohai Sea is affected by the cold Siberian air every winter, which causes the sea surface temperature of the Bohai Sea to be significantly lower than that at the same latitude (Zhang et al., 2016; Donlon et

al., 2012). In addition, the sea surface salinity of the Bohai Sea is about 30 PSU, which is the lowest in the entire coastal waters in China (Yan et al., 2020). It means that the Bohai seawater freezes before reaching the maximum density. Therefore, it even more easily convects and loses heat just before freezing.

- The paper mostly deals with sea ice, and neglects the Bohai Sea circulation. Is it mostly barotropic and driven by tides or is there a contribution of baroclinic effects, is there haline or thermal stratification? Basically, if the low salinity of the Bohai Sea is essential to explain the sea ice cover, then it is crucial to know what are the processes that drive the salinity balance of the Bohai Sea. Additionally could you provide estimates of how much flow comes from the Yellow Sea and leaves, is the circulation mostly cyclonic or is it not even geostrophic perhaps? This point is important because we need to understand if the long term sea ice cover trends are only driven by atmospheric forcing, or if changes in ocean circulation and/or river runoff can also affect the sea ice cover through the long term changes of SSS. And of course, we want to know how the model compares with estimates of this circulation.

Thank you for your comment. We have detailed this part to a larger extent. A new section 3.2.3., including plotting the simulated currents at surface and lower layer and estimating the monthly mean water volume exchange at the Bohai Strait as suggested, was added as suggested. Further analysis of the vertical profile of temperature and salinity in later parts will help understand the thermal or haline stratification in the Bohai Sea.

3.2.3 Sea current

The circulation in the Bohai Sea is mainly barotropic and results from the combined effects of tides and winds (Li et al., 2015). The simulated monthly mean current velocities at the surface and 16 m depth in February and August are shown in Fig. 5. The monthly mean current velocities are calculated based on hourly model output during August 2012 and February 2013. The figure shows that both the sea surface and 16 m depth current are usually less than 0.4 m s^{-1}. Due to the blocking effects of the bays, currents are weak at the head of the three bays, which is consistent with the observations by Chen et al. (1992). The surface currents in the Bohai Sea also show apparent seasonal variations. In August, relatively strong currents flow from the southeastern part of Liaodong Bay to the southern Bohai Strait with a solid outflow to the Yellow Sea. Specifically, the current field distribution at Bohai Strait shows that the inflow is mainly in the narrow channel in its northern part, which agrees with the observations of Wan et al. (2015). Also, Lin et al. (2011) suggested that persistent winds drive a cyclonic coastal current into the northern Yellow Sea, and one branch of the current enters the Bohai Sea at the northern Bohai Strait, which transports warm and saline water from the Yellow Sea.

The monthly mean water volume exchange at the Bohai Strait (see Fig.1) based on hourly model simulations during August 2012 and February 2013 are also calculated to evaluate the model's performance. The Bohai Sea water exchange with the Yellow Sea is weak due to its half-closed shape and a relatively independent circulation system. The model results show that the inflow from the Yellow Sea to the Bohai Sea in August reaches 6.9×10^4 m^3 s^{-1}, almost double than that in February (3.5×10^4 m^3 s^{-1}), which lies in the range of 5×10^3 to 8×10^4 m^3 s^{-1} indicated by Bian et al. (2016). Our results show that the outflow exists in both months (August: 8.3×10^4 m^3 s^{-1}; February: 6.5×10^4 m^3 s^{-1}), with a larger amount than the inflow. The net flow appears to be outflow both in winter

and summer, which is consistent with other model simulation results (Lin et al., 2002; Ji et al., 2019).
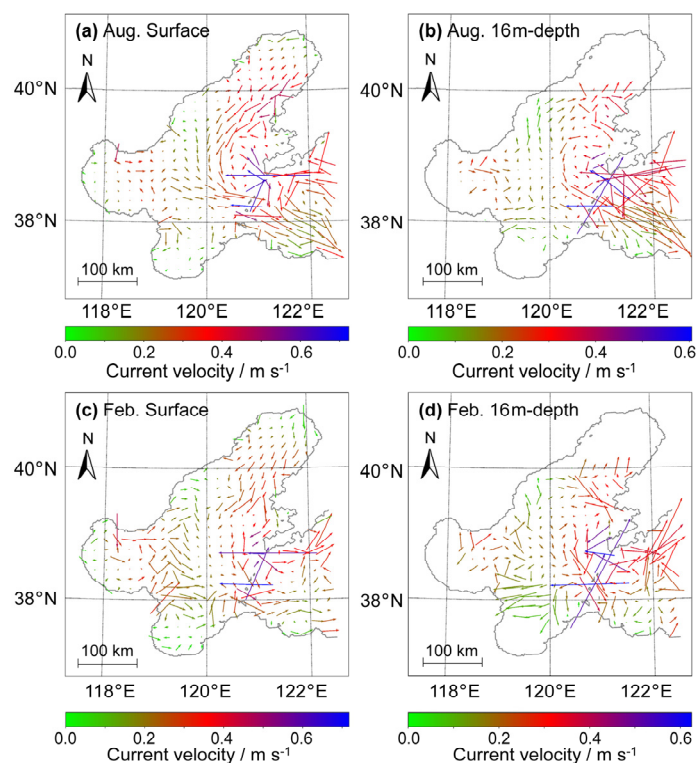

Figure 5: Simulated monthly mean current velocities at surface and 16 m depth in August 2012 and February 2013. The monthly mean current velocities are calculated based on the outputs with hourly intervals.

- Although the paper lacks a proper presentation of the Bohai Sea hydrography, there is an extensive presentation of ORCA025 used at the OBCs. Could you just replace it with a simple reference?

This part has now been shortened as suggested. The extensive presentation of ORCA025 is replaced by the reference of Bernard et al. (2006). We have only kept the updated forcing datasets, which are often overlooked by model users and worth mentioning in this part.

- As mentioned before, the Nemo-Bohai settings are very difficult to read. But I understood you use the Blanke & Delecluse TKE turbulence scheme. This choice is a bit odd in such a configuration but perhaps does not matter too much if the tidal mixing kills any form of stratification, and therefore I would understand that this is not much of a concern. The background vertical diffusivity is also very high, but perhaps it does not matter too much for the same reasons. However, could you show some T/S profiles and comparison with data in some of the deepest areas? Having the right density profile close to the OBCs is an important feature to get the right amount of estuarine circulation. This part would be of course a lot easier to understand if you have first presented a proper hydrography of the Bohai Sea as mentioned before.

We have revised the garbled symbols to improve the readability of the revised manuscript. Indeed, we agree that comparing the temperature and salinity vertical profiles between the model and observations is very valuable. We have followed you and added the T/S profile figures (Fig. 6 and Fig. 7) accordingly, and relevant texts have been added to the new section 3.2.4:

NEMO-Bohai and observed water temperature and salinity profiles along the transect AB (see Fig.1) are shown in Fig. 6 and Fig. 7, respectively. Observations are from the atlas by Chen (1992), which is based on data from the 1950s to 1990s. The temporally closest 5-year period from 1995 to 2000 of NEMO-Bohai simulations was selected for model-observation comparisons. Common features are found both in the model and observations. The Bohai Sea waters are vertically well-mixed in autumn and winter, and they have a remarkable homogeneous vertical distribution for both temperature and salinity. In spring and summer, thermal stratification occurs with a significant cold-water core at depth, eventually eroded in autumn. As apparent in Fig. 6 and Fig. 7, the stratification in shallow coastal waters is generally homogeneous. Similar features were reported by Wang et al. (2008), who analyzed the seasonal variations of the vertical profiles in the Bohai Sea.

The model results, however, show some discrepancies compared to the atlas. Although the model reproduces the summer saline stratification, it is weaker than in the atlas. Nonetheless, Li et al. (2015) reported that the summer salinity stratification in the Bohai Sea is possibly weaker than in the atlas, with an observed top-to-bottom salinity difference of 0.6 PSU. The modeled salinity distribution along with transect AB during summer is possibly affected by the high vertical diffusivity. In the north part of the transect, which corresponds to the northern Liaodong Bay, a negative salinity bias is visible compared to the atlas. In addition to the reasons mentioned in section 3.2.2, inaccuracies in the ETOPO1 bathymetry, especially in the low water depth region seen from Fig. 6 and Fig. 7, may also cause these underestimations.
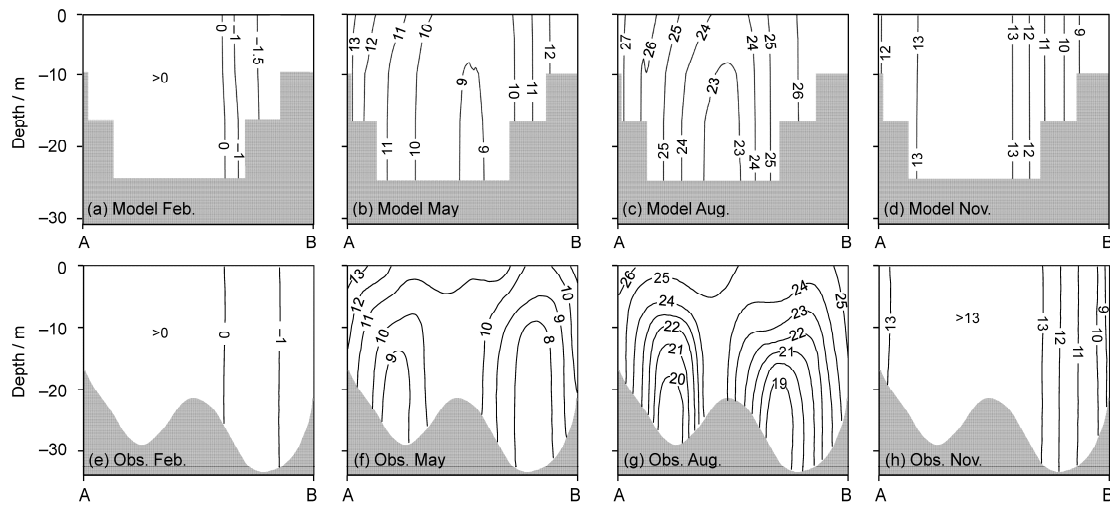

Figure 6: Comparison of vertical profiles of water temperature (°C) along with transect AB (locations shown in figure 1) between NEMO-Bohai (a-d) and the atlas (Chen, 1992) (e-h) in February, May, August, and November.
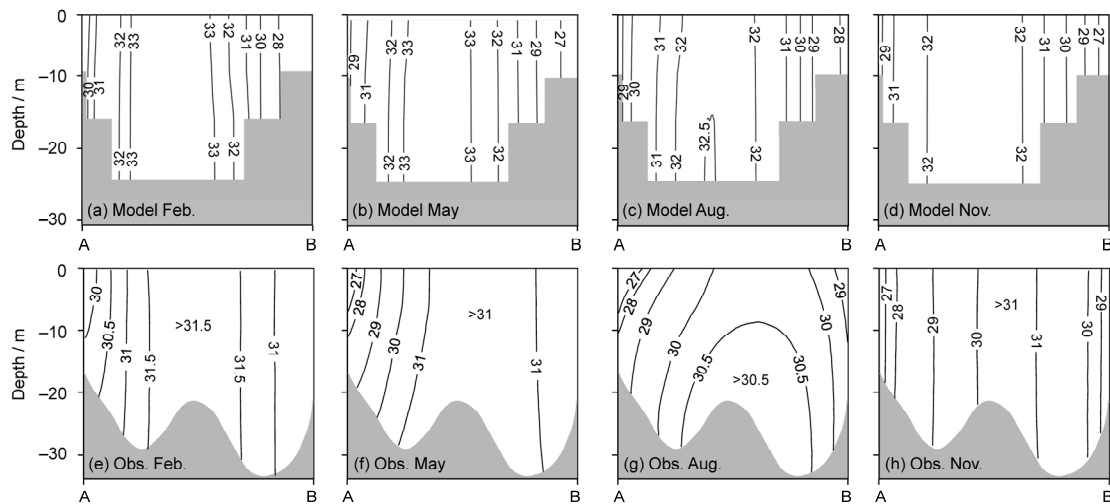
Figure 7: Similar to figure 6 but for salinity (PSU).

The lack of stratification in summer is possibly caused by the high setting of vertical diffusivity in the model, as you indicated, and sensitivity experiments with different turbulent energy closure schemes will be further studied in the future.

- The validation part of the ocean follows the weakness of the paper I think, it lacks some interest of the ocean. Please provide statistics when they are useful, especially for SSH: standard deviation of both model and observations, correlation, and mean square root error. And in this part you can also provide a comparison with S/T profiles which will allow to check the turbulence and the circulation. Having statistics on salinity or temperature is not really essential if we don't understand why, and there are only measurement stations along the coast.

Basically please extend the validation of the ocean with explanation of the biases rather than a purely descriptive approach.

Indeed, thanks to this remark. We have included more information on the validation part. Specifically, in terms of SSH, we have added extra validation results and a table (see Table 2) in section 3.2.1 with more information such as standard deviation, correlation, mean absolute errors, and root-mean-square error. As for the comparisons of S/T profiles, we have added the figure and text in the new section 3.2.4 accordingly.

To better explain the results of the model-observation comparison, we have expanded the explanation of the biases as suggested. For example, we have supplemented the possible reasons for SSH deviation in section 3.2.1 and addressed the reasons for the vertical profile discrepancy in section 3.2.4.

In section 4 come some results about hydrography, which we have to assume are correct based on a validation that is rather light.

We have added the comparisons of temperature and salinity vertical profiles between NEMO-Bohai and the atlas, as well as the validation of currents. In addition, more explanations for model biases are proposed in section 3. Our main finding is that the NEMO-Bohai reproduces the main variables of ocean and sea ice well.

We agree that sea ice is significantly related to atmospheric and possible oceanic forcing in such shallow water. It would be fascinating to understand what drives the lack of significant trends of sea ice cover or volume, so here we have added a new section 4.2.3 to explore the potential regional climate driving factors on the evolution of sea ice as suggested. As you indicated, the local temperature is the controlling factor for the sea ice evolution in the Bohai Sea. In addition, we have further defined the oceanic effects on the sea ice by investigating the spatial correlation between daily sea ice concentration and vertically integrated ocean heat/salt content (see newly added Fig. 21). Our main finding is that the interannual variability of Bohai Sea ice is more dominated by heat content than salt.

We have employed the English Language Editing service to improve the language presentation.

Corrected. The certain terms in Nimbus Mono L Font are garbled, and we have revised these weird symbols accordingly in the revised manuscript.

Thanks for your careful work on our manuscript. We have checked the mathematical notation and unit notation one by one and corrected them according to manuscript guidelines required by Copernicus Publications. Regarding the unit of salinity, we have replaced it with the unit of PSU as suggested.

We have revised this line to clarify this point.
It is noticeable that there is a lag in modelling sea ice formation during the early freezing period compared to satellite observations.

The text has been revised.

Reference

Bernard, B., Madec, G., Penduff, T., Molines, J. M., Treguier, A. M., Le Sommer, J., Beckmann, A., Biastoch, A., Böning, C., Dengg, J., Derval, C., Durand, E., Gulev, S., Remy, E., Talandier, C., Theetten, S., Maltrud, M., McClean, J., and De Cuevas, B.: Impact of partial steps and momentum advection schemes in a global ocean circulation model at eddy-permitting resolution, Ocean Dynam, 56(5), 543-567, 2006.

Bian, C., Jiang, W., Pohlmann, T., and Sündermann, J.: Hydrography-physical description of the Bohai Sea, J Coast Res, 74, 1-12, 2016.

Chen, D. X.: Marine atlas of Bohai Sea, Yellow Sea and East China Sea: Hydrology, Ocean Press, Beijing, China, 1992.

Ding, D.W.: Introduction to sea ice engineering (in Chinese), Ocean Press, Beijing, 1999.

Donlon, C. J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E., and Wimmer, W.: The operational sea surface temperature and sea ice analysis (OSTIA) system, Remote Sens Environ, 116: 140-158, 2012.

Ji, C. Z., Li, K., Yu, B., Dong, L., and Liu, Q. R.: The multi-time scale variations of water exchange across the Bohai Strait, Oceanol Limnol Sin (in Chinese), 50, 24-30, 2019.

Li, Y., Wolanski, E., and Zhang, H.: What processes control the net currents through shallow straits? A review with application to the Bohai Strait, China, Estuar Coast Shelf S, 158, 1-11, 2015.

Lin, X., Wu, D., Bao, X., and Jiang, W.: Study on seasonal temperature and flux variation of the Bohai Strait, Journal of Ocean University of Qingdao (in Chinese), 32(3), 355-360, 2002.

Lin, X., Yang, J., Guo, J., Zhang, Z., Yin, Y., Song, X., and Zhang, X.: An asymmetric upwind flow, Yellow Sea warm current: 1. New observations in the western Yellow Sea, J Geophys Res-Oceans, 116(C4), C04026, 2011.

Su, H. and Wang, Y.: Using MODIS data to estimate sea ice thickness in the Bohai Sea (China) in the 2009-2010 winter, J Geophys Res-Oceans, 117, C10018, 2012.

Wan, K., Bao, X., Wang, Y., Wan, X., Li, H., and Liu, K.: Barotropic current fluctuations coupled with sea level drawdown in Yellow and Bohai Seas, Chin J Oceanol Limn, 33(1), 272-281, 2015.

Wang, Q., Guo, X., and Takeoka, H.: Seasonal variations of the Yellow River plume in the Bohai Sea: A model study, J Geophys Res, 113, C08046, 2008.

Yan, Y., Uotila, P., Huang, K., and Gu, W.: Variability of sea ice area in the Bohai Sea from 1958 to 2015, Sci Total Environ, 709, 136164, 2020.

Zhang, N., Wu, Y., and Zhang, Q.: Forecasting the evolution of the sea ice in the Liaodong Bay using meteorological data, Cold Reg Sci Technol, 125, 21-30, 2016.