Comments on the MS by Ye Liu, Lars Axell, and Jun She

An assessment of the variability in temperature and salinity of the Baltic Sea from a simulation with data assimilation for the period 1990 to 2020 https://doi.org/10.5194/egusphere-2024-3283

The MS presents the application of Baltic Sea physics reanalysis system, based on the NEMO-Nordic ocean model engine set up on the 4 km (2 nautical mile) grid. The model is driven by atmospheric forcing from the UERRA reanalysis product, open boundary data from the northeast Atlantic barotropic surge model, and daily river discharge taken from a dataset by the EHYPE model. Observational data (T/S profiles, SST from remote sensing) are assimilated using the Local Singular Evolutive Interpolated Kalman (LSEIK) filter. The reanalysis system has been developed within the activities of the Baltic Monitoring and Forecasting Centre (BalMFC) of the Copernicus Marine Service (CMEMS), where the authors play an active role. Presentation of the reanalysis system, including a validation study, is followed by an analysis of mean, variability, trends and seasonal cycle of temperature and salinity.

The MS is interesting, but before publication I recommend clarification of the following points.

Thank you very much for your positive and helpful comments. We have addressed all the comments. Specifically, we add a detail comparison between this reanalysis data to CMEMS Baltic reanalysis in discussion. We believe this revision has improved the clarity of our argument and addressed the concern raised.

A) Relation of the present reanalysis data to the data downloadable from the Copernicus Marine Service

Baltic Sea Physics Reanalysis data, downloadable from the CMEMS portal (https://data.marine.copernicus.eu/product/BALTICSEA_MULTIYEAR_PHY_003_011/description, https://doi.org/10.48670/moi-00013) has growing use in research, reflected in numerous scientific publications. Presently the reanalysis 1993-2023 has been upgraded to 2 km (1 nautical mile) resolution. For the users of CMEMS reanalysis data it remains unclear whether this publication presents the same or alternative data set. It should be explicitly written in the MS and reflected in the section Code and Data availability.

Thank you for this valuable comment. We clarified the relationship of this dataset in this study and the CMEMS Baltic Physical reanalysis product in the revised manscript and provided a detailed comparison of these two datasets in discussion section 5.3:

The two datasets—one from this study and the other from CMEMS Baltic physical reanalysis—both provide valuable insights into the Baltic Sea's physical conditions, but they differ significantly in terms of model setup, atmospheric forcing, data assimilation methods, and the choice of assimilated satellite products of SST.

- This study uses NEMO-Nordic 1.0 with 2 nm resoluation (Hordoir et al. 2019) and the current CMEMS product (BALTICSEA_MULTIYEAR_PHY_003_011) is based on Nemo-Nordic 2.0 with 1 nm resoluation (Kärnä et al. 2021).
- The study's simulation is forced by atmospheric data from the UERRA reanalysis (11 km) and ECMWF ORAS4/5 reanalysis products along with a barotropic surge model for the northeast Atlantic. In contrast, the CMEMS product is forced by the ERA5 dataset (31 km) and uses daily mean values from the CMEMS North West Shelf multi-year product at lateral boundaries.

- The study uses LSEIK (Local SEIK) for data assimilation, while the CMEMS product uses LESTKF (Local Ensemble Transform Kalman Filter). Different from the CMEMS Baltic reanalysis with LESTKF method, this study uses a multivariate EOF method to generate a sample ensemble of background error covariances, which enhances the identification of key large-scale spatial and temporal variability patterns while reducing dimensionality and noise. This method allows for sampling various combinations of patterns from the ensemble space, enchancing the ensemble diversity and improving DA accuracy, leading to a more reliable simulation. Futhermore, a varying observation error with water depths in this study is good to adjust the water deeper than thermocline/ halocline. The study assimilated the satellite observations from OSISAF and IceMap SSTs, whereas the CMEMS Baltic physical reanalysis used Copernicus Marine Service L3S SST multi-year observations (SST_BAL_PHY_L3S_MY_010_040).

These differences could lead to variations in the oceanographic predictions for the Baltic Sea, with potential impacts on temperature, salinity, and ice dynamics. Both datasets offer valuable information.

In case the analyzed data set is an alternative to the CMEMS downloadable data, the present reanalysis data originals should be made available. The MS refers only to post-processed data used for drawing the figures: https://doi.org/10.5281/zenodo.13961375. Also, comparative statistics of the present data and of https://doi.org/10.48670/moi-00013 should be presented.

We thank the referee for this comment. The reanalyzed dataset of this study isn't an alternative to current CMEMS reanalysis product. The primary goal of our study is to present a reasonable dataset and assess the variability of temperature and salinity in the Baltic Sea. We referenced the post-processed data to provide readers with context about the datasets used in this study. The original data are also available from the authors upon request. This study is not solely focus on the validation of the dataset. Therefore, it is not appropriate to do a fully comparative statistical analysis between the present dataset and the CMEMS Baltic reanalysis product. However, we do include a comparison of the quality of the two datasets. The text has been revised accordingly:

”Although, both this reanalysis and the Copernicus Marine Serivce Baltic Sea Physical Reanalysis (CBSPR, BALTICSEA_MULTIYEAR_PHY_003_011) covered the past three decades, they differ significantly in model setup, atmospheric forcing, DA method, and assimilated satellite observation sources. Unlike this study, CBSPR is based on NEMO-Nordic 2.0 with a resolution of 1 nm (Kärnä et al. 2021), as well as a coarser atmospheric forcing (ERA5 dataset with 31 km resolution), and boundary conditions from the CMS North West Shelf multi-year product. This study uses a multivariate EOF method to generate a sample ensemble of background error covariances, which enhances the identification of key large-scale variability patterns while minimizing noise and reducing dimensionality. This method allows for sampling various combinations of patterns from the ensemble space, enhancing the diversity of the ensemble and improving DA accuracy, leading to a more reliable simulation. Furthermore, the study assimilated the satellite observations from OSISAF SST and IceMap, whereas the CBSPR used CMS SST observations (SST_BAL_PHY_L3S_MY_010_040). When compared to the CBSPR, the sea level anomaly in this study exhibits a stronger correlation with observations, except in Visby, Talinn, Grena, and Viken. A comparison of CFs revealed both datasets have comparable salinity quality at the same Baltic stations. However, there are notable discrepancies in SBS in both the southern Bothnian Sea and the southwestern Bothnian Bay. In the southwestern Bothnian Bay, the quality of SBS reported in this study was classified as good, whereas the CBRP was classified as poor. Conversely, in the southern Bothnian Sea, the CBSPR data was of higher quality than the SBS in this study. Regarding temperature, the CBSPR was of high quality across all stations, while this study reported slightly lower quality in the southern Bothnian Sea, though still within acceptable limits. In conclusion, all reanalyses provide valuable insights into the physical conditions of the Baltic Sea. "

B) Observational data sets:
The MS mentions the use of T/S profile data adopted from the SHARK and ICES data bases. Other types of in-situ T/S data (ferrybox, gliders, Argo floats etc) available from https://doi.org/10.48670/moi-00032 and used for https://doi.org/10.48670/moi-00013 are not referred. If the use of observational T/S data is indeed limited, it needs to be clarified.

Thank you for pointing this out. We clarified the limitation of the study in its use of observations in the revised text:
" it is important to acknowledge that our research is constrained by the exclusion of certain available observations for assimilation. For example, we haven't assimilated the Baltic Sea- In Situ Near Real Time Observations (INSITU_BAL_PHYBGCWAV_DISCRETE_MYNRT_013_032), consist of level 2 data sourced from various platforms such as ferry boxes, gliders, and Argo floats. However, the presented study has already assimilated the T/S profile observations from important Baltic mooring stations in the Baltic Sea- In Situ Near Real Time Observations. To the surface satellite data, we utilize a coarse level 2 satellite product that aligns more closely with the horizontal resolution of the model employed in this study. Further, the satellite SST assimilated in current Baltic CMEMS reanalysis serves as a benchmark for validating the reanalyzed SST of this study."

C) Statistics at different depths over the whole basin",
The results contain curious salinity data at different depths, not straightforward for oceanographic interpretation. Namely, mean and min/max values of salinity at the surface and at the 60 and 100 m depth, presented in Table 1 reveal that at the surface, mean salinity is 8.18 psu (from 5.74 to 9.94), but in the depth salinity is much lower, 4.12 psu at 60 m depth and 4.79 psu at 100 m depth, with min/max range from 6.32 to 9.05 and 7.48 to 9.94 psu, respectively. This makes the vertical profile hydrostatically strongly unstable that is not in agreement with oceanographic concepts. While the mean salinity values are not understandable, the time series analysis of trends (Fig. 9, Fig. 11) and seasonal cycle (Fig. 12) also cannot be trusted.
Temperature calculations obviously have the same problems.

The sub-chapter "4.2 Trends and variability of temperature and salinity" should be fully recalculated and rewritten. Conclusions from 2 to 4 should be revised as well. To achieve meaningful information for oceanography, perhaps the revised presentation could follow some aspects of the sub-basin approach.

We have carefully recalculated the results. In the revised manuscript, the calculation area was restricted to the Baltic Sea region i.e., the sub-basin of the Baltic Sea region east of 13 °E longitude, and the shallow transition zone between the Baltic Sea and the North Sea were removed. The mean and min/max values of salinity in the depth salinity is 7.48 psu (from 6.54 to 8.48 psu) at 60 m and 9.16 psu (from 8.61 to 9.63 psu) at 100 m, respectively. The reason that the mean values of bottom salinity (7.39 psu) are smaller than those at 60 m /100m is that the shallow zone is included in the bottom average, but not the intermediate depths. In the revision, we used standard deviations to show uncertainty in the trend statistics. For clarity, both the table and the graph are revised to:

Table 1. The temperature and salinity variability in the Baltic Sea over the period 1990-2020.

Parameter	Trend [year $^{-1}$]	Mean	Maximum	Minimum
SST [ºC]	0.037±0.010	8.16±0.60	20.08±1.54	0.67±0.54
T60 [ºC]	0.044±0.008	4.16±0.55	6.76±0.52	2.31±0.62
T100 [ºC]	0.051±0.006	4.77±0.54	5.53±0.57	4.09±0.51
SBT [ºC]	0.041 ±0.008	5.34±0.53	10.76±0.51	1.96±0.49
SSS [PSU]	-0.004±0.002	5.83±0.10	6.50±0.10	5.01±0.20
S60 [PSU]	0.026±0.003	7.48±0.28	8.48±0.42	6.54±0.13
S100 [PSU]	0.049±0.005	9.16±0.51	9.63±0.55	8.61±0.51
SBS [PSU]	0.015 ±0.003	7.39±0.19	8.34±0.26	6.54±0.15

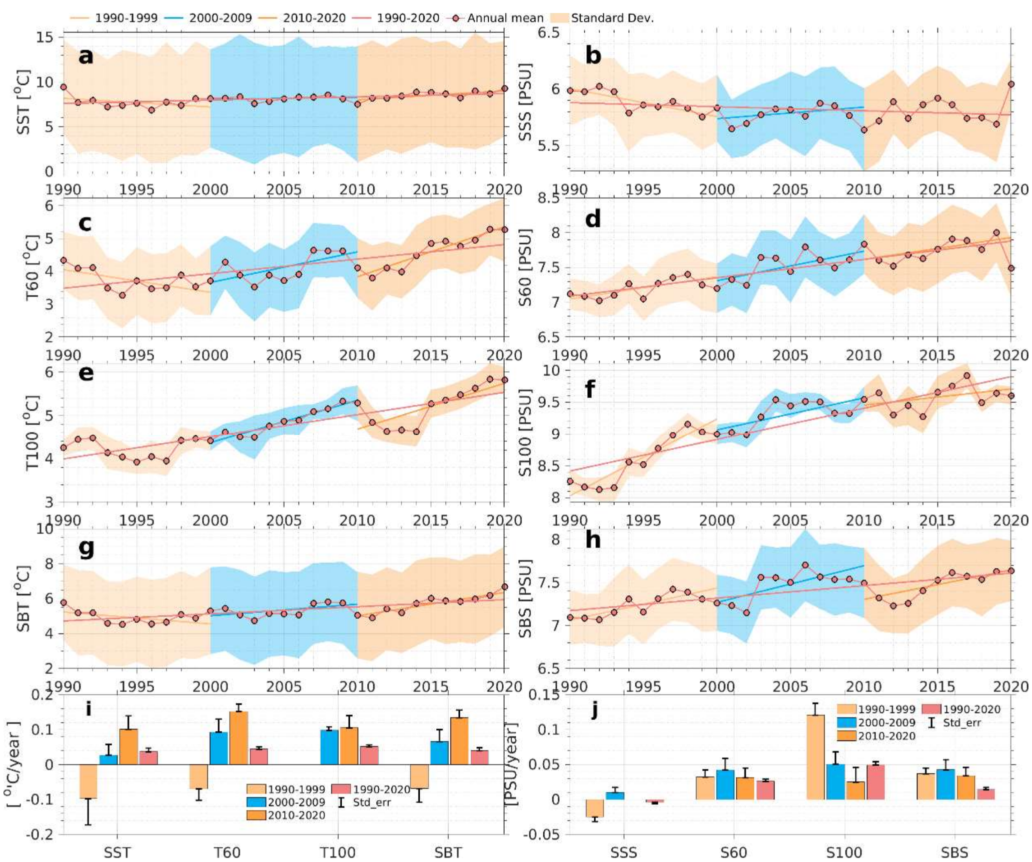

Figure 9. The annual mean temperature (left panel) and salinity (right panel) at surface (a,b), 60 m(c,d), 100 m (e, f), and the bottom (g, h) of the Baltic Sea for the period 1990-2020 and their linear decadal trends (i, j). Linear trends are showed by solid lines and the standard deviations are showed by the shaded area.

D) Advancing oceanographic knowledge

If the authors wish to focus the MS on the assessment (instead of data assimilation), the oceanographic aspect of the study has to be strengthened. The publication list is dominated by references to modelling and data assimilation studies. These topics are also dominant in the discussion; one part out of four parts is devoted to comparison with other studies on long-term variability in the Baltic Sea.

This study seeks to estimate a reliable and gabless variability of temperature and salinity at various depths within the Baltic subbasins using a reanalysis dataset from 1990 to 2020. We first evaluate the reliability of the reanalysis dataset, followed by an analysis of the variability of temperature and salinity from the dataset. To verify our findings, we compare our results with those from observational data.

We updated the references and added some refercenes in the topic of the Baltic variability (Dutheil et al, 2023, Meier et al. 2023, Mohrholz, 2018, Zalewska et al. 2023; Kankaanpää et al. 2023; Bittig, et al. 2024).

we also reconstructed the discussion section: 1. Reanalysis bias and Model baises, 2. Comparison with other reanalysis studies of the Baltic Sea, 3. Comparison with other studies on the variability in temperature and salinity of the Baltic Sea, 4. Implications for Climate Change and Biodiversity.

In the chapter of results, the sub-chapter “4.1 Validation of the simulation results” is clear in content and it is well written. Regarding variability in temperature and salinity of the Baltic Sea over decadal scales (from the title of the MS), sub-chapter “4.2 Trends and variability of temperature and salinity” has serious data processing problems as indicated above. After making technical corrections, the authors should consider how to advance the oceanographic knowledge of the Baltic Sea beyond the already many publications on that topic.

We are very grateful for your positive comment and provide a good comment. We apologize for the mistake in the manuscript and recalcualted our results accordingly. We restricted the compute area to the Baltic Sea. (also see our response to the comment C above)

Assessing the variability in temperature and salinity of the Baltic Sea through a simulation with data assimilation is a significant advancement in oceanographic knowledge of the Baltic Sea. We highlight our contribution to the Baltic Sea community

- **Improvement of model predictions:** By assimilting observational data (e.g., satellite data, in-situ measurements) into model predictions, the study shows a method to improve accuracy of model precditions in the Baltic Sea by providing more accurate, reliable, and comprehensive models of the sea's dynamics. As a result, the accuracy of the presented dataset is significantly better than that of the dataset from model alone.
- **Assessing T/S trends by combining models and observations**: As Stockmayer and Lehmann (2023) highlighted, discrepancies between observed and simulated trends emphasize the importance of combining models and observations for accurate trend analysis. Most of the Baltic variability studies were focused on surface or bottom trends, and only a recent study explored the intermediate temperature trends from in-situ data (Liblik and Lips 2019) and modeling (Dutheil et al. 2023). This study fills this gap by examining continuous temperature and salinity trends across four depths in the Baltic Sea over the past three decades. This is

particularly important for the intermediate waters, where observations are sparse, model biases limit T/S changes assessments.

- **Applications and impact on future research:** With this comprehensive dataset, researchers can now analyze temperature and salinity at any depth in the Baltic Sea. Our dataset also extends predictions beyond short-term observations, making it a key reference for studies on the Baltic Sea's health and sustainability, especially in the intermediate waters.
- **Environmental implications:** Our study highlights a combination of warming and increased salinity stratification, suggesting that the Baltic Sea is experiencing more pronounced layering between surface and deep waters. This enhanced stratification may reduce oxygen transport to deeper layers, exacerbating hypoxia in deep basins and negatively impacting marine ecosystems and fish populations. Additionally, the stronger halocline could hinder nutrient mixing, potentially disrupting primary productivity and biogeochemical cycling. These changes may, in turn, affect food web dynamics and alter fish populations.
- **Policy and management recommendations:** By reliable quantifying the variability of temperature and salinty in the Baltic Sea, this study helps decision-makers in understanding how these factors influence oceanographic conditions. Our findings offer essential insights for policy development in coastal management, marine ecosystem protection, pollution control, and fisheries sustainability. Based on our results on Baltic Sea warming and salinity trends, we recommend that fishery management and coastal planning incorporate strategies for adapting to these changes, alongside enhanced monitoring of ecosystem shifts tied to warming and salinity changes.

Some technical comments

1) Presently, the text is overloaded with different numbers. The sub-sub-chapters are too much as mere explanations of figures, starting “Figure 9 and Table 1 provide …”, “Figure 10 shows …”, “Figure 11 reveals …”, “Figure 12 provides …”.

We have revised the text and reduced the number of numbers used.

2) The statement “This is the first attempt to estimate the T/S variability at various depths within the Baltic sub-basins from a reanalysis perspective” (lines 62-63) is not clear; what would it bring new/different to the previous estimates.

We have revised the text:

“This study is to conduct a quantitative assessment of a physical reanalysis of the Baltic Sea for the period 1990–2020. It aims to provide reliable predictions for long-term and seasonal variations of temperature and salinity (T/S) in the Baltic sub-basins during this period. By utilizing the reanalysis dataset, we demonstrated a reliable and gapless variability of T/S at various depths within the Baltic sub-basins for the past three decades. ”

3) It is not directly said what are the numbers in Table 1 in terms of averaging intervals.

We have removed Table 1:

4) The statement in lines 340-341 is not understandable, what is new: “This indicates that the temperature variability is larger at the surface than at other depths”.

We revised the text:

”Compared to the surface waters, the subsurface waters exhibited a less variability in annual mean temperature.”

5) Fig. 3, it is not clear where to find “number of profiles at the selected monitoring stations(c)”

We thank the referee to reminding us this vague description. We clarify the caption of Figure 3 :

” Cost function values of sea temperature (a) and salinity (b) from the reanalysis simulation at the selected monitoring stations (see Fig.2) from 1990 to 2020.”