Dear Reviewer:

Many thanks to the reviewer for the number of useful comments that will help to significantly improve the quality of the final version of this manuscript. We have addressed all your concerns and have resulted in significant improvements to the manuscript. The detailed response to each comment can be found in the attached document.

Best wishes

All authors

RC2: Referee William Pringle

General comments:

This study uses a parameter estimation methodology implemented in an unstructured mesh global tide and surge model (GTSM v4.1) to estimate bathymetry and the bottom friction coefficient to reduce modeled tide errors at the coast. The parameter estimation methodology was developed by the authors in Wang et al. (2021, 2022), which focused on computational efficiency and memory efficiency of the parameter estimation algorithm by using model order reduction in space (Coarse Incremental Calibration) and in time (Proper Orthogonal Decomposition onto principal modes of variation). In those previous works the authors focused on perturbations to bathymetry to improve tide solutions. Therefore, the predominant novelty of this study is the simultaneous perturbation of the spatially varying bottom friction coefficient along with the bathymetry in a global model to assimilate tide observations and estimate these two parameters.

Although the tide errors of GTSM v4.1 are small and reasonable, I think the manuscript needs to do a better job of discussing why the errors in this model cannot be made as small as FES2014. Precisely what is the difference in data assimilation (DA) methodology that makes the TPXO/FES-type DA models able to give more accurate results overall than the parameter estimation technique used here? Also, what are the remaining major obstacles to further reducing tide error using the presented parameter estimation technique?

One of the reasons outside inaccurate bathymetry and unknown dissipation parameters for tide solution discrepancy could be errors associated with hydrodynamic simulation of the tide without concurrent simulation of meteorological-driven flow (surge). In shallow waters the estimation of bottom friction coefficient could be quite different in certain regions if surge is included due to nonlinear interaction. Furthermore, two recent related studies by the authors (Wang et al., 2021, 2022) also just investigate tide-only simulation, so to bolster this study the authors should consider adding in simulation(s) with meteorological forcing to show the sensitivity of tide solutions to concurrent surge simulation, especially since one of the main stated advantages of GTSM over FES/TPXO is the ability to simulate tide and surge together ("combined tide and surge model").

The other comment I have is on subdomain selection. In this study the two regions selected, Hudson Bay and European Shelf, are based on high tidal dissipation, which makes some sense. However, it is not clear how the subdomains within those regions are selected, although it appears to based on the authors' intuition (Line 284: "The region of Scotland, the Faro Islands and Shetland have mountainous ocean bathymetry, where expect to a higher bottom friction coefficient"). Have the authors investigated sensitivity to subdomain selection/size? Perhaps a spatial clustering type analysis or other could be used to more objectively find the suitable subdomains.

Response: Thank you for the valuable comments.

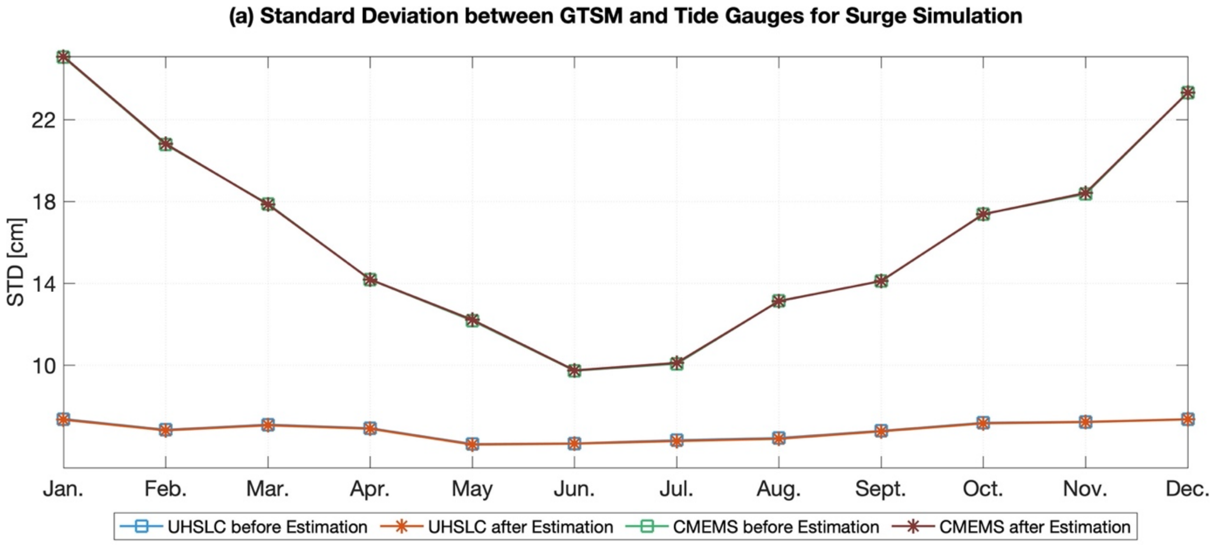
The possible reasons that our estimation is slightly worse than FES2014 are: The estimation in FES2014 gives an accurate estimate of the tide, but the underlying model is only used as a first guess or weak constraint. As a result of this choice, the tidal solution can be very accurate, but the result is a relatively static dataset. In contrast, the calibration of GTSM in this paper uses the model as a strong constraint. This results in a calibrated model that can used as a regular non-assimilative hydrodynamic model. For example we use the GTSM model for storm-surge forecasting and studying the impact of sea level rise; both are not possible with FES2014. Moreover, in our paper we aim to provide the solutions for accurate estimation when there is a lack of sufficient observations. Therefore, FES2014 uses more observations such as satellite altimetry data, tide gauge data into the estimation. But GTSM use the FES2014 dataset as the observations in the deep ocean which sharply reduces the complexity of data preprocessing. Description has been added into the sections Introduction and Conclusion of the manuscript.

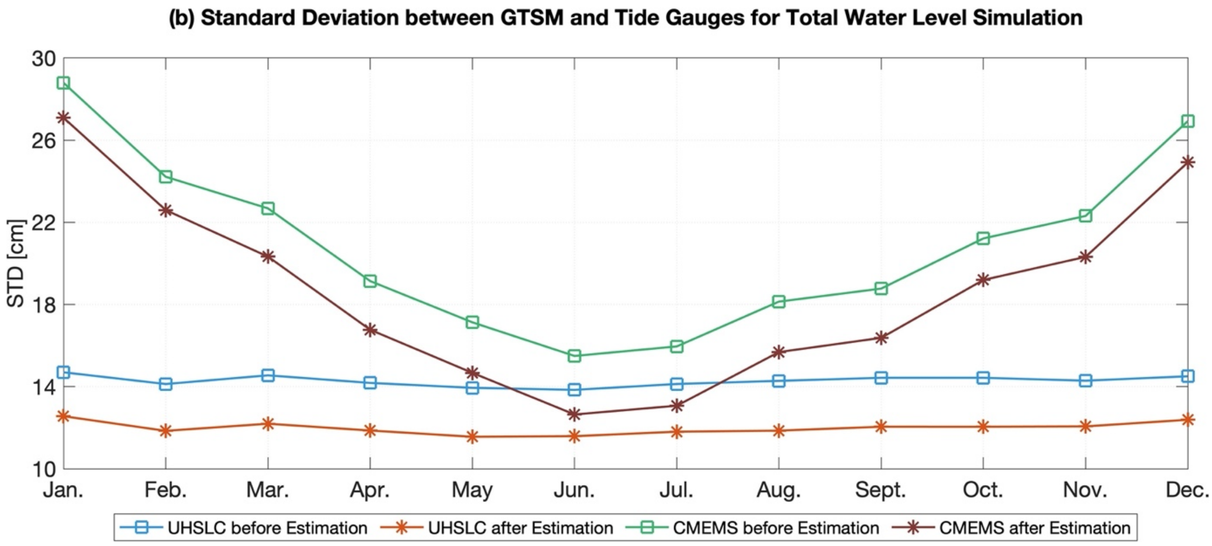
To better assess the estimation performance, we compared model performance and the FES2014 with the Bottom Pressure Recorder (BPR) gauge data in the deep ocean. FES2014 is slight better than GTSM and the main reason could be FES2014 uses BPR data in the assimilation process while BPR dataset is independent to our estimation procedure. In the shallow water we use part of the CMEMS dataset as observations and some FES2014 data in the region of scarce stations. FES2014 assimilated 600 tide gauges with a relatively homogeneous geographical distribution. We observed that FES2014 in the shallow water cannot perform as accurate as that in the deep ocean (Stammer et al., 2014). Therefore, it will also affect the estimation accuracy. In addition, FES2014 also corrected the internal tide coefficient and LSA (load and self-attraction) in the estimation process. When comparing with the estimation technique, FES2014 used the SpEnOI (Spectral Ensemble Optimal Interpolation) data assimilation algorithm and we use the computation and memory efficient DUD algorithm. Since estimation performance depends on many factors such as the number of observations, parameter size and so on. We don't think we can directly compare the assimilation techniques.

We add the major obstacles to further reduce tide errors in the conclusion of the paper:

"The remaining major obstacles to further reducing tide errors using the presented parameter estimation technique are (1) When we consider to include satellite altimetry data especially in the shallow water to the estimation process, the accuracy of harmonic tidal analysis to the satellite altimetry has to be assessed, which would require complex preprocessing. (2) The influence of sea ice on the tide is currently not yet included into the model. However, the seasonal modulation from sea ice can affect the model performance (Kagan & Sofina, 2010; Müller et al., 2014), because sea ice exerts additional frictional stress on the surface. In our parameter estimation experiment, we observed that in the Canadian archipelago, higher bottom friction coefficients are estimated. This is probably caused by a lack of dissipation by sea ice. However, the estimated bottom friction coefficients do not result in a good agreement with the seasonal dynamics. A possible solution is to include the sea ice modeling in the GTSM, and the sea ice coefficient will also become an uncertain source to estimate. This will also require measurements that properly represent modulation of the tides over the seasons. Preliminary products of this type are starting to appear (Bij de Vaate et al., 2021). "

Secondly, we add an experiment to compare the model derived surge before and after the estimation with the tide gauge data (UHSLC and CMEMS data). The surge simulation is performed for the year 2014 with the meteorology forcing (wind and air pressure conditions) from ERA5 reanalysis data set. The spatial-averaged monthly standard deviation of surge and total water-level simulation is shown in the following figure.





We add the following paragraph to the Section Numerical Experiment and results of the paper:

"The standard deviations before and after the estimation show minor difference in Figure 11a. It is consistent with findings in our previous research to estimate bathymetry for GTSM (Wang et al., 2021). The error are generally larger in the areas with stronger tide in the shallow waters. This makes the absolute value of the STD very dependent on the tide gauges that are used. In the UHSLC dataset, the locations are spread over the planet. The CMEMS dataset focuses on the European Shelf with stronger winds in winter.

In general, surge comparison shows that surge is not sensitive to the bathymetry and bottom friction but strongly affected by the wind and air pressure conditions. This conclusion is also supported by Chu et al., (2019) to access the sensitivity of surge in the east China Sea (their Figure 13). In our study, even though surge simulation keeps the same accuracy after the estimation, the water level forecast accuracy is improved because of the improvement of tide representations, which is significantly demonstrated in the Figure 11b. Therefore, the bottom friction and bathymetry estimation improves the model derived water level forecast ability in the coastal areas."

Moreover, thanks for your suggestion. It is a good idea to use a spatial clustering type analysis to find the suitable subdomains for parameters in the future. In this study, our selection of bottom friction subdomain is based on the following three rules: (1) subdomain is in the region with large tide energy dissipation; (2) subdomain is selected in which the observations are well-distributed. (3) Considering the sea bed topography, subdomain is set to divide the region that would have different values of coefficient.

Point-by-point comments:

Line 52: "We found only one application [of data-assimilation to estimate parameters] at a global scale (Lyard et al., 2021)…". Although it is a very recent study available as a pre-print, Blakely et al. (2022) also tries to "optimize" parameters for internal tide and bottom friction in a global tide model using the TPXO tide solutions, which I think would be worth referencing and comparing to in this manuscript.

Response: We have included a reference to Blakely's paper into the Introduction of the Manuscript as follows:

"Blakely et al. (2022) adjusts the bottom friction and internal tides friction in 41 subdomains to better represent the tide in the ADCIRC model, allowing the bottom coefficient to vary with the subdomain gives a significant improvement on model performance."

Line 59: "The sensitivity to bottom friction is very small in deep water, but is often the most sensitive parameter in shallow water". Can the authors find some reference(s) for this? For one, I suggest Zaron (2017) here who presents a friction number that denotes the relative importance of the friction parameter in the momentum balance, and I think Zaron's paper will also provide material that can be used to improve the ideas presented in this part of the introduction.

Response: Thank you for the suggestion. We have added a reference to the paper of Zaron into the Introduction of the Manuscript as follows:

"Zaron (2017) denoted the relative importance of the friction parameter in the momentum balance in the Sea of Okhotsk based on the sensitivity test results."

Section 2.1: There are numbers quoted for the tidal energy dissipation, 3.7 TW; 2.39 TW for bottom friction and 1.12 TW for internal tides. Do these numbers always stay constant no matter the bathymetry and bottom friction parameters being estimated? I also suggest to put these numbers in context with other tidal dissipation values from the literature as well to give an idea to the reader of the typical ranges and inter-model variability.

Response: The values of tidal energy dissipation before and after the estimation are consistent. After the estimation, the tidal energy dissipation is 2.44TW for the bottom friction and 1.33TW for the internal tides. The total tidal energy dissipation is 3.77TW. It implies that the estimated bottom friction coefficients are reasonable. Moreover, this value also matches the findings of other researchers with a global dissipation of around 3.7TW either from the model simulation or measurement analysis (Egbert and Ray, 2001; Green and Nycander, 2013；Munk and Wunsch, 1998).

We added the description into the section Parameter to Estimate of the paper as follows:

"The value of tide energy dissipation matches the findings of other researchers with a global dissipation of around 3.7TW either from the model simulation or measurement analysis (Egbert and Ray, 2001; Nycander, 2005; Munk and Wunsch, 1998)."

Line 111: "[The Chezy formulation] is important for hydrodynamic conditions". What does this mean?

Response: We rewrite the sentence as: “Bottom friction term is important to determining hydrodynamic conditions and sediment transport process.”

Lines 114-116. These statements require more detail. Exactly how is the internal tide friction term corrected for layer thickness in the salinity/temperature dataset (what does this mean?). How was the retweaking of the bottom friction and internal tide coefficients done and how does this compare to this study which is trying to find improved bottom friction coefficients?

Response: We rewrite the sentence in the section Global Tide and Surge Model of the paper as follows:

“GTSMv4.1 contains an updated internal tide friction term that is related to the buoyancy frequency of the stratified ocean. In the previous version of GTSM, the layer thickness variability was not taken into account properly and this was fixed in the dataset for GTSMv4.1. The correction coefficient for this improved dataset is derived again and the spatial uniform bottom friction was set to a value found more often in literature.”

Lines 118-119: States the RMSE is without the bias difference. Does just mean the RMSE used here is the standard deviation of the error? I notice Figure 9 panels have the title of “Standard Derivation …” which maybe should read standard deviation. Please clarify.

Response: We remove the bias difference from model and observations. Because the simulation is only related to tide and the mean difference could be from the different reference plane of observation. We also corrected the title of Figure 9 to be “standard deviation”.

Lines 128-129: “However, the spectral tide model cannot describe the interaction between different tide components in shallow waters.” What is meant by “describe” here? In Le Provost & Lyard (1997), which is the underpinning of the FES model, the methodology considering tide component interaction through linearization of the bottom friction term is presented. So while it’s true that the tide component interaction in a spectral model cannot be computed “exactly” like in a time-stepping shallow water model, some interaction through the bottom friction term can be accounted for.

Response: we have rephrased the sentence in Section Global Tide and Surge Model of the paper as follows:

“However, the spectral tide model cannot exactly compute the tide components interaction, even though some methodologies such as representing the interaction through linearization of bottom friction term are presented (Le Provost & Lyard, 1997).”

Section 4.1.2: Parameter estimation results: Only relative changes to the parameters are shown but I think it would be interesting information for readers to know the initial and final values of the bottom friction coefficients (which may be compared to bottom friction values obtained in Blakely et al., 2022).

Response: The initial value of the bottom friction coefficient is 62.5. After the estimation, the bottom friction values are shown in the following figure.

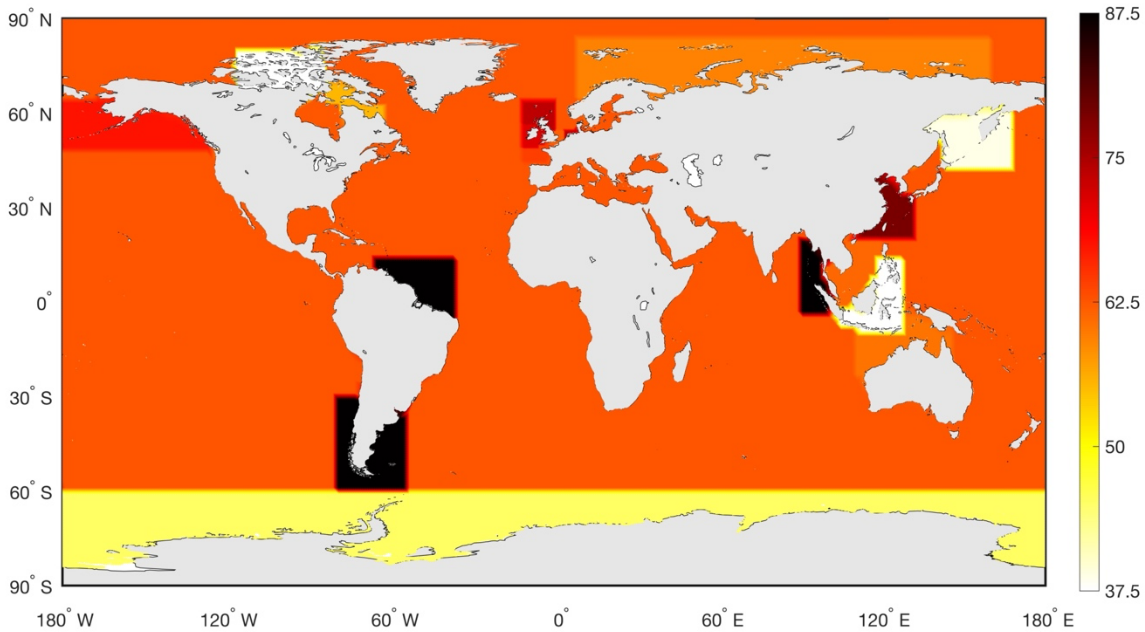


Figure: Bottom friction coefficients after the parameter estimation of GTSM.

We didn't compare the difference of bottom friction values between our study and that in Blakely et al., 2022 because we use the Chezy formula while Blakely use the Manning formula. The coefficient C in the Manning formula is related to the depth H as $C = {H^{1/6}}/{n}$.

Lines 491-492: "Tide representation in shallow waters benefits from the optimization of bottom friction coefficient, contributing to a more accurate water level forecast when including wind and air pressure conditions for surge simulation". This is more than likely correct but is not a conclusion that can be straightforwardly made from the study. If, as I mention in the general comments, this study considers the sensitivity of the parameter calibration to tides with concurrent simulation of surge, it should help to provide stronger evidence for this statement.

Response: We compared the model simulated surge before and after the estimation, the results are shown in the reply to the general comment.

Technical corrections:

Line 126: What is SLA?

Response: It is the Self-attraction and loading. In Lyard et al. (2021), they call it loading and gravitational self-attraction (LSA). I have rephrased the sentence in the Global Tide and Surge Model of the paper as follows:

"FES2014 uses the Spectral Ensemble Optimal Interpolation (SpEnOI) algorithm to estimate the bottom friction coefficient, the internal tide drag coefficient, the bathymetry and the LSA (loading and gravitational self-attraction). It leads to an accurate data collection of 34 tidal components."

Table 1/Line 127: TPOX09 to TPXO9.

Response: corrected.

Lines 355-369: In these two paragraphs a confusing terminology of the RMSE being reduced to X% is used. I think it's easier to understand how much the RMSE was reduced BY.

Response: We have rephrased these sentences using “reduced by”.

References:

Blakely, C. P., Ling, G., Pringle, W. J., Contreras, M. T., Wirasaet, D., Westerink, J. J., Moghimi, S., Seroka, G., Shi, L., Meyers, E., Owensby, M., & Massey, C. (2022). Dissipation Processes in an Unstructured Mesh Global Tidal Model. Under review at Journal of Geophysical Research: Oceans. https://doi.org/10.1002/essoar.10509993.1

Le Provost, C., & Lyard, F. (1997). Energetics of the M2 barotropic ocean tides: an estimate of bottom friction dissipation from a hydrodynamic model. Progress in Oceanography, 40(1), 37–52. https://doi.org/10.1016/S0079-6611(97)00022-0

Wang, X., Verlaan, M., Irazoqui Apecechea, M., & Lin, H. X. (2021). Computation-Efficient Parameter Estimation for a High-Resolution Global Tide and Surge Model. Journal of Geophysical Research: Oceans, 126, e2020JC016917. https://doi.org/10.1029/2020JC016917

Wang, X., Verlaan, M., Irazoqui Apecechea, M., & Lin, H. X. (2022). Parameter Estimation for a Global Tide and Surge Model with a Memory-Efficient Order Reduction Approach. Under review at Ocean Modelling.

Zaron, E. D. (2017). Topographic and frictional controls on tides in the Sea of Okhotsk. Ocean Modelling, 117, 1–11. https://doi.org/10.1016/j.ocemod.2017.06.011

Chu, D. , Zhang, J. , Wu, Y. , X Jiao, & Qian, S. . (2019). Sensitivities of modelling storm surge to bottom friction, wind drag coefficient, and meteorological product in the east china sea. Estuarine, Coastal and Shelf Science, 231, 106460-.