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

RC1 Anonymous referee #1

General comments

This manuscript deals with data assimilation-based parameter estimation of bathymetry and bottom friction coefficient to improve coastal accuracy in a global tide model. Ultimately, the purpose of this study is to improve tidal prediction accuracy of their GTSM through data assimilation using FES2014 and tidal gauge data. Regarding this point, I wonder if the GTSM in tidal prediction can be better than the FES2014. If not, what is advantage of use in the GTSM? Just computation and memory efficiency? In addition, with respect to the parameter estimation of bathymetry, I suggest that the authors compare their model initial bathymetry and corrected bathymetry with that of FES2014. These results may provide useful information on their input bathymetry's suitability.

In general, I do not think that the manuscript is well written because of a lot of unclear and repeated explanations. The authors should be avoid report style and should make the manuscript concise with stressing their novel scientific findings. Additionally, the location map with names should be added for readers to easily understand locations mentioned in this study. Therefore, as it is, it seems to me that this manuscript is not appropriate to publish in Ocean Science.

Response: Thanks for the review and suggestions. It seems that we have not made our motivation and choices clear enough. FES2014 is an assimilative tide model, that comes in the form of a gridded data collection with the resolution of 1/16°. It consists of 34 tidal components to provide tidal representations. This 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. A consequence of using the model as a strong constraint is that this dramatically reduces the number of degrees of freedom for the assimilation, leading in general to larger differences with the observations. Comparing FES2014 to the calibration of GTSM, the aim is a different type of result. While we aim for a good accuracy, it is likely that the calibrated GTSM produce less accurate tides but can be used for a wider range of applications. These remarks discuss the assimilation aspect only, but other factors, such as the resolution, quality of the input data and the physics included in the model, also contribute to the accuracy of the final result. Finally, also the amount and quality of the assimilated observations influences the accuracy. FES2014 assimilates a large number of observations, both from remote sensing and in-situ achieving a very high accuracy in deep waters, which is why we have selected it as a data-source for our calibration.

This description to explain the difference between FES2014 and our research has been added in the Introduction of the manuscript as follows:

“We found only one parameter estimation application at a global scale (Lyard et al., 2021), where altimetry tides and tide gauge data are assimilated into the T-UGO tide model. The uncertainty for the model, is partly based on parameter uncertainty, such as bed friction, but the result is in the form of 36 tidal components in a gridded data collection with the resolution of 1/16°, called FES2014. It can provide accurate estimate of tide, but the result is a relatively static dataset because the underlying T-UGO tide model is only used as a first guess or weak constraint. In contrast, we propose a different approach to calibrate GTSM in this paper, using the model as a strong constraint. This results in a calibrated model that can be 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.”

We also add one paragraph to discuss the accuracy of FES2014 and the estimated GTSM in the conclusion of the manuscript.

“However, the purpose of the calibration of GTSM is different from that of FES2014. GTSM is used as a strong constraint. A consequence of it is that this dramatically reduces the number of degrees of freedom for the assimilation, leading in general to larger differences with the observations. It is likely that the calibrated GTSM produce less accurate tides but can be used for a wider range of applications. These remarks discuss the assimilation aspect only, but other factors, such as the resolution, quality of the input data and the physics included in the model, also contribute to the accuracy of the final result. Finally, also the amount and quality of the assimilated observations influences the accuracy. FES2014 assimilates a large number of observations, both from remote sensing and in-situ achieving a very high accuracy in deep waters, which is why we have selected it as a data-source for our calibration.”

The bathymetry datasets used in the T-UGO tide model are GEBCO and ETOPO, but after applying data assimilation to the model, the FES2014 tidal constituents are not fully consistent with the bathymetry. Therefore, we have not attempted to compare the bathymetry. Besides, we have contacted the authors for the availability of the bathymetry data, but until now we didn’t receive it.

We have carefully checked the manuscript and made a number of changes to improve the structure and readability, as listed:

1) We have checked the grammar of the manuscript. Some repeated explanations are removed and redundant descriptions to make the manuscript more concise.
2) We have emphasized the scientific findings in the section Introduction, Experiment and Conclusion.
3) The section Experiment have been rewritten. A one-year simulation experiment comparing the surge and total water level representations before and after the estimation was added into the subsection “Monthly Time-series Comparison” of the paper. Results show that 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.
4) The location map with names has been added to the Figure 3 and Figure 4 in the Manuscript. It also can be found in the point-to-point response.

Some specific comments follow to help the authors address their manuscript’s weakness:

1. Title

- The authors should change the title to contain key words (e.g., Data assimilation based parameter estimation of bathymetry and bottom friction coefficient to improve coastal accuracy in a global tide model).

Response: Thank you for your suggestion. The title is changed to: Data-assimilation based parameter estimation of bathymetry and bottom friction coefficient to improve coastal accuracy in a global tide model

2. Abstract

- I think that the authors need to include the specific parameter estimation scheme name used for an efficient computation and memory efficiency.

Response: We now call the parameter estimation scheme: Time-POD based coarse incremental parameter estimation. This name has been adjusted in the paper.

3. Section 1 (Introduction)

- On p. 3 lines 68-69: The authors need to clearly explain how the energy dissipation by bottom friction in shallow water also change the tides in the adjacent deep ocean.

Response: Thank you for your suggestions. We have added the following explanation into the Introduction of the manuscript.

"Though the dissipation by bottom friction predominantly occurs in shallow water, this will also change the tides in the adjacent deep ocean when the tide propagates from the coastal regions to the nearby deep ocean. The range of affected areas are related to the topography and tide dissipation (Detailed analysis see Section 4.1)."

This is illustrated by the result of experiments with perturbed bottom friction coefficient in one coastal subdomain, as the following figure shows.

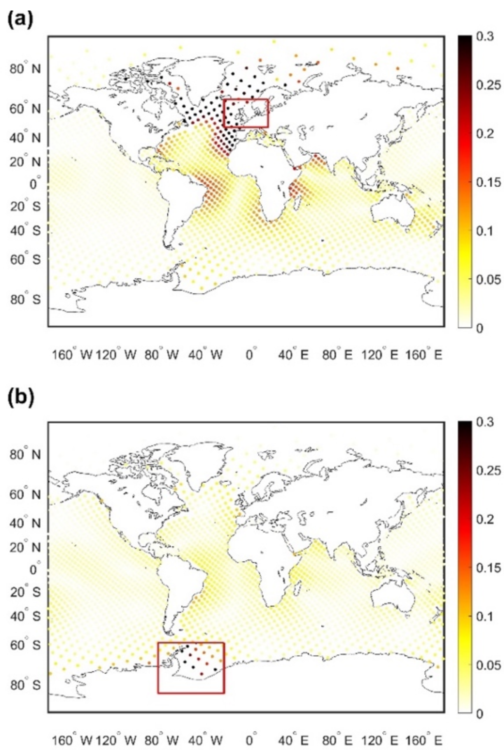

Figure: RMS of the difference between the initial model and model with perturbed bottom friction in the European Shelf (a) and Southern Ocean (b) in [m]. Bottom friction coefficients in the red boxes are perturbed with 20%.

We can observe that the influence of the tidal dissipation on the shelf is much wider than the shelf itself, so in the parameter estimation we now get better results by coupling the calibration of bathymetry and friction. The RMS in Figure a is obviously larger than Figure b. It is consistent with the fact that more tide energy dissipation occurred in the European Shelf than in the Southern Ocean.

4. Section 2 (Method)

- The authors should make it clear whether they adjusted the model bathymetry or not. Because GEBCO 2019 is sourced from navigation chart data, the chart datum can be not mean sea level but lowest astronomical tide (LAT) or a datum as closely equivalent to this level. Thus, particularly in tidally dominated shallow coastal regimes, the GEBCO 2019 should be adjusted. I also recommend that the authors compare their model depth data with that of FES2014 which can be provided as request.

Response: Our GTSM model uses Mean Sea Level (MSL) as its vertical reference. To be consistent, input datasets should be converted to the same vertical reference. We applied corrections to both GEBCO and EMODnet datasets. For the GEBCO dataset, the MSL-LAT correction was calculated with the FES2012 dataset and applied everywhere. Although GEBCO does not explicitly defined the reference as LAT, our experience is that much of the data is referenced to LAT, which is consistent with the IHO standard for nautical charts.

We add a description of the reference datum in the section Method of the manuscript:

"For consistency between the vertical reference of the model and that of the data, all bathymetric data are corrected using the Mean Sea Level (MSL) as its vertical reference datum."

In addition, the question referred to the comparison of model depth data with that of FES2014 has been answered in response to the general comments.

- On p. 4 line 108: Need to put reference for Chezy formula.

Response: Chézy formula was developed by the French engineer, Antoine Chezy. We now include a reference in the paper (Manning, 1891.)

Manning, R., "On the flow of Water in Open Channels and Pipes." *Transactions Institute of Civil Engineers of Ireland, vol. 20, pp 161-209, Dublin, 1891, Supplement, vol 24, pp. 179-207, 1895*

- On p. 4 line 110: As far as I know, the value of C varies with depth range. Need to check it and clarify it.

Response: There are several types of formula to define C in the bottom friction term. We use the Chezy formulation, C is defined as the constant coefficient. For the manning friction formula, the value of C is dependent on the depth: $C = \sqrt[6]{D}/_{n}$, where D is the depth and n is the user-defined coefficient.

- On p. 4 lines 117-118: As the authors showed in Table 1, even though the resolution of TPOX09 is higher than that of FES2014, they used FES2014 without any clear explanation. With respect to this point, they need to clearly explain the reasons. Did they calculate RMSE of TPOX09 and compared with that of FES2014?

Response: The accuracy of FES2014 and TPX09 is comparable even though TPXO9 has a higher resolution than FES2014. Stammer et al., 2014 assessed several model performances including FES2012 and TPXO8. The following table shows the comparison from the paper of Stammer et al., 2014.

RMS Model Differences (cm) Against Deep-Ocean Bottom Pressure Recorder (BPR) Stations										
	Q1	O1	P1	K1	N2	M2	S2	K2	RSS	M4
FES12	0.216	0.309	0.355	0.471	0.342	0.658	0.407	0.223	1.120	0.115
TPX08	0.153	0.310	0.181	0.442	0.201	0.523	0.338	0.151	0.893	0.069
RMS Model Differences (cm) Against Shelf Water Tide Stations										
European Shelf										
FES12	0.88	0.82	0.71	1.19	1.39	3.71	1.94	0.63	4.82	2.22
TPX08	0.88	0.72	0.46	1.21	1.58	3.85	1.70	0.74	4.87	0.35
Elsewhere										
FES12	0.80	1.00	0.89	1.51	1.58	3.33	2.30	1.02	4.96	0.98
TPX08	0.82	1.00	0.82	1.47	2.00	3.50	1.93	1.12	5.07	0.88
RMS Model Differences (cm) With 56 Coastal Tide Gauges										
FES12	0.32	0.89	0.61	1.65	1.74	6.60	2.27	0.77	7.50	1.49
TPX08	0.43	1.13	0.93	2.01	3.34	15.65	7.79	2.21	18.10	1.68

In the deep ocean and shelf regions, FES12 and TPXO8 have comparable RMS and RSS. In the coastal regions, TPXO8 is less accurate than FES12. We agree that the RMS statistic is probably not a good general descriptor, since one or two poor performing stations can dominate the results. But the results show that they have comparable accuracy even though TPXO8 has higher accuracy than FES12. Therefore, we use FES2014, which is the successor of FES12, as observations in this study.

- On p. 5 lines 130-135: Need to explain the advantages and disadvantages of DUD compared the other data assimilation algorithms.

Response:

DUD is one of the parameter estimation algorithms working in an iterative ensemble approach. Its advantages and disadvantages are:

1) Compared to the variational data assimilation algorithms, DUD is a method similar to Gaussian-Newton but derivative-free. The derivative-free approach can reduce the complexity of the estimation process.
2) DUD perturbs each parameter to generate the ensemble. While other ensemble algorithms usually estimate with an ensemble size smaller than the number of parameters and subsequently with a limited estimation accuracy due to the small

ensemble size. However, DUD is not suitable for the system with a large number of parameters.

We add some description in the Section 2.2 “Parameter Estimation Scheme” of the Manuscript:

“Compared to the variational data assimilation algorithms, the derivative-free approach in the DUD can reduce the complexity of the estimation process. The size of ensembles in DUD is equal to the number of parameters, that ensures sufficient degree of freedom for parameter estimation, while other ensemble algorithms normally use an ensemble size smaller than the number of parameters and subsequently leads to a limited estimation accuracy. However, DUD is not suitable for the estimation with large number of parameters.”

- Figure 1a: If possible, in Figure 1a, the authors need to put numbers used in y-axis of Figure 1b as area identification number. - Figure 1b: put titles of x-axis and y-axis.

Response: We have added the region identification numbers and polygons in Figure 1. The titles of x-axis and y-axis in Figure 1b are also added. The updated figure is as follows:

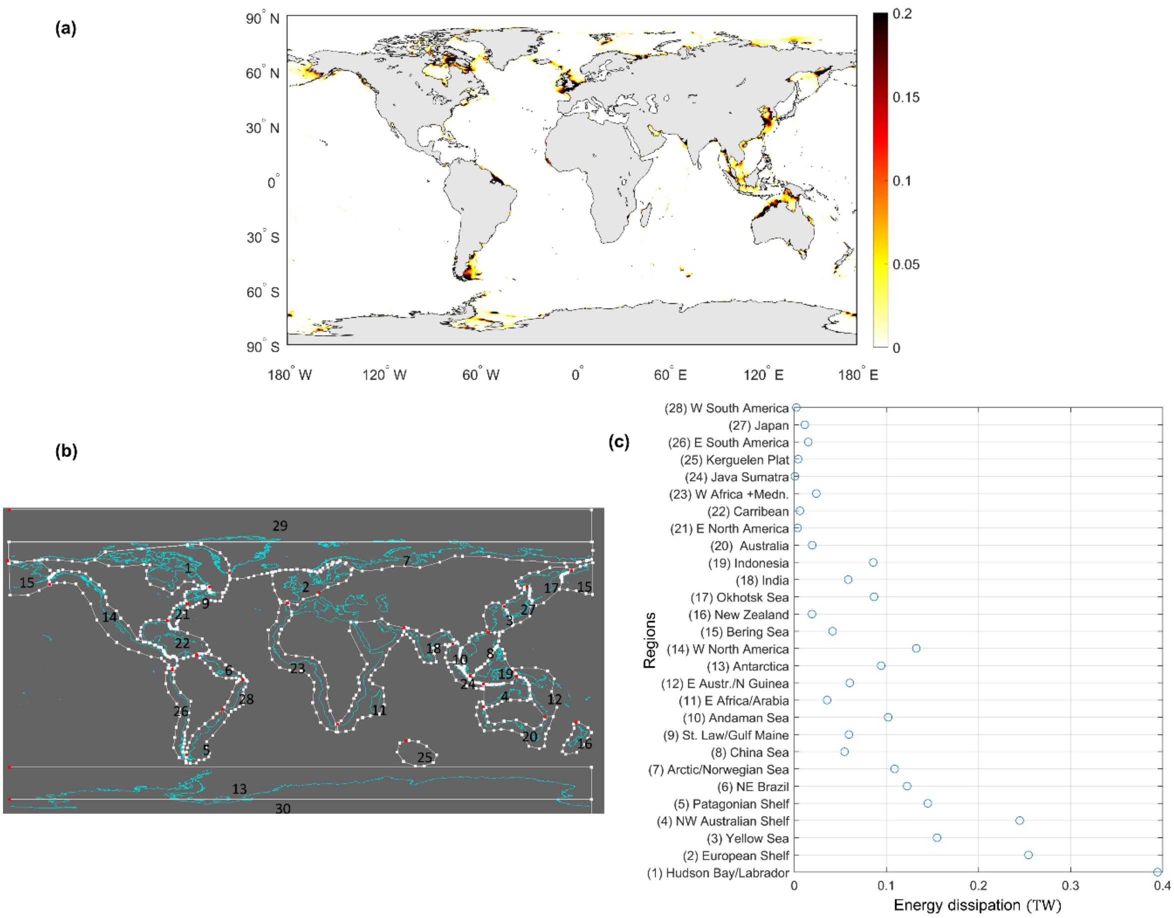

Figure 1. Bottom friction energy dissipation in initial GTSMv4.1 (a) Global distribution [Unit:W/m^2]; (b) Area identification; (c) Area-integrated energy dissipation [Unit:TW].

- On p. 9 lines 216-219: The authors need to rewrite the sentences. Is there any reason to choose the specific year of 2014? Did you predict tides of 2014 along with tidal harmonic analyses?

Response: The selection of the year 2014 is based on the analysis of tide gauge data. The available tide gauges vary in different years. The reason for choosing 2014 is for it has the largest number of stations with available data. In this paper, GTSM is simulated over the whole year of 2014 for the tidal harmonic analysis.

We rewrite the paragraph in the Section 2.3.2 Observation Network, as follows:

"We select the year 2014 for the model analysis because the available tide gauges varying in different years and year 2014 has the largest number of stations. Tide analysis is performed in the tide gauge data from CMEMS and UHSLC dataset for the year 2014 with the TIDEGUI software, a matlab implementation of approach by Schureman (1958) and we visual inspect the tide and surge representations. After the analysis and quality control, we obtained 237 locations in the UHSLC dataset and 297 locations from the CMEMS dataset. In the deep ocean, we generate about 4000 time series from the FES2014 dataset to ensure enough observations for estimating bathymetry in the year of 2014. These observations are evenly distributed and located in the deep ocean with a depth larger than 200m."

5. Section 3 (Estimation of Bottom Friction Coefficient)

- Figure 3a: What do the numbers (1, 2, and 3) in Figure 3a mean?

Response: The numbers (1,2 and 3) are just used to indicate the three subdomains we defined in the Hudson Bay/Labrador areas. It simplifies the reference in the discussion.

- On p. 12 lines 262-263: The authors need to put names including Foxe Basin, Hudson Strait and Ungave Bay in a location map.

Response: We have added the region names into the caption of this Figure:

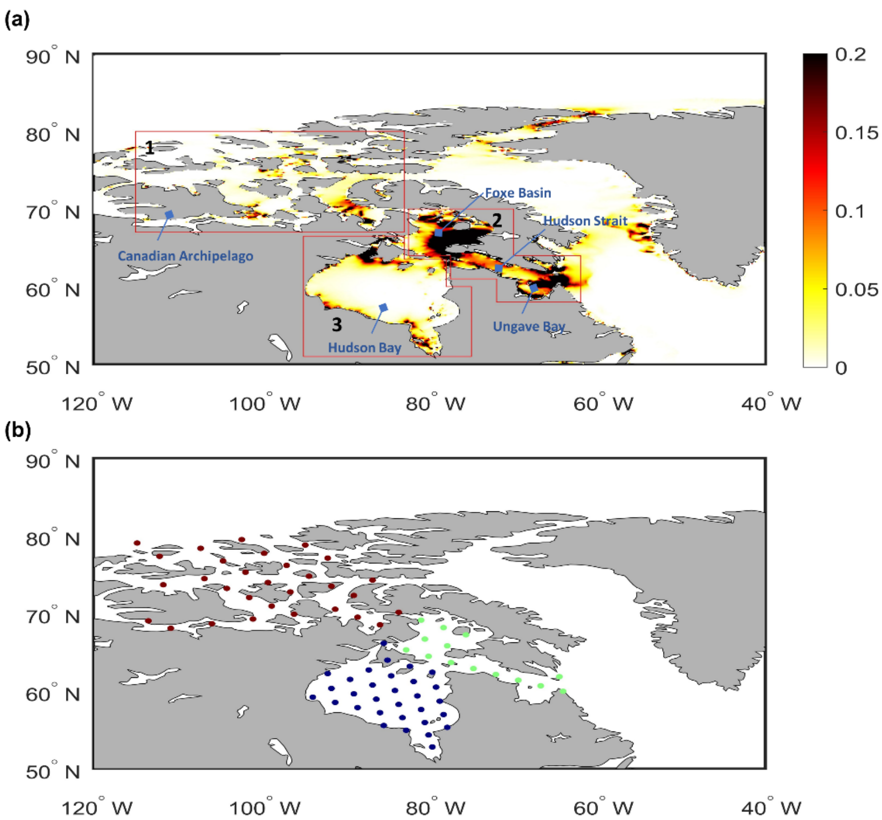

Figure: (a) Bottom friction energy dissipation per square meter of the Hudson Bay/Labrador in GTSMv4.1 [unit:W/m^2] and bottom friction coefficient subdomains (red boxes). Subdomain 1: Canadian Archipelago; Subdomain 2: the combination of Foxe Basin, Hudson Strait and Ungave Bay; Subdomain 3: Hudson Bay; (b) FES2014 observation distribution: Points in different subdomains have different colors.

- On p. 12 lines 264-269: The authors should rewrite these sentences to make them clear. What kind of “parameters” do you mean? What is “the form of tide components”? Does it mean “harmonic constants for tidal constituents”? How long do you use “model output of time series”?

Response: The parameters in this section are the bottom friction coefficient. “The form of tide components” means the harmonic constants for tidal constituents. The time series used for harmonic tide analysis is one year (the year of 2014) and for the estimation 1 month model simulation is used. We have reshaped the sentences in the paper as follows:

“The available observations are from the arctic stations but only include four major tidal components. In theory, harmonic tide analysis can be performed for the model output and it is possible to estimate parameters with the model output of harmonic constants for tidal constituents, but accurate tide analysis needs a time series of a year, which would increase the computation demand. For example, Wang et al., (2021b) reported that a full time series of 1 month is sufficient for an accurate parameter estimation. However, the yearly tide analysis would increase run times by a factor of 12. This is not feasible for us at the moment. Therefore, we choose to use the model output of time series covering 1 month in the estimation process and 1 year for harmonic tide analysis. The arctic stations can be used for the model validation.”

- On p. 12 lines 284-285: The authors need to put names such as Scotland, the Faro Islands and Shetland in a location map. There were twice “The region of Scotland, the Faro Islands and Shetland have mountainous”. Remove one.

Response: Sorry, it is a mistake. We have corrected it and put the names are in the figure.

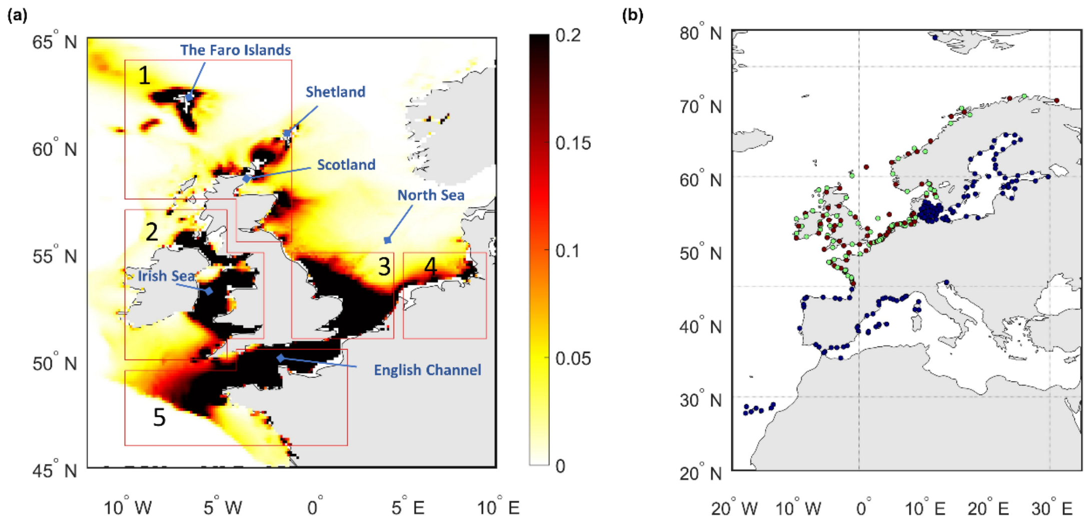

Figure 4. (a) Bottom friction energy dissipation per square meter across the European Shelf in GTSMv4.1 [unit:W/m^2] and bottom friction coefficient subdomains (red boxes). Subdomain 1: The combination of the Scotland, Faro Islands and the Shetland; Subdomain 2: Irish Sea; Subdomain Subdomains 3 and 4: North Sea; Subdomain 5: English Channel; (b) CMEMS observation distribution: points in red are data used for calibration, points in green are used for validation and points in blue are not used.

6. Section 4 (Numerical Experiment and Results)

- On p. 14 lines 312-319: I think that these sentences were mentioned in previous sections.

Response: Thank you for your suggestion, we removed the repeated information and reshaped paragraph as follows:

“We selected a period of one month, September 2014 for the estimation runs. We found that simulation time length covering one month is sufficient for tide calibration when using high-frequency time series with 10 minutes sampling (Wang et al., 2021b).”

- On p. 14 line 315: Is there any reason to select “September” and “2014” for a period of one month?

Response: The selection of the year 2014 is based on our analysis of the largest number of available stations. And the month “September” is because the sea ice model is not included in the GTSMv4.1 and in September, there is no ice coverage so we can ignore the effect of sea ice.

We have added a description of this into the paper:

“In addition, sea ice in the Arctic Ocean is not modeled in the GTSM, but it has seasonal changes to the tides (Inger et al., 2021). Performing the experiment in the September can minimize the impact of sea ice to the model because of no ice coverage in the September.”

- On p. 15 line 328: Are there any reason or reliable source to give the values of 5% and 20% uncertainty for bathymetry correction factor and bottom friction coefficient, respectively?

Response: Bathymetry is considered uncertain here because only a fraction of the ocean seabed has been surveyed, and the remaining errors are significant. Tozer et al. (2019) reported an estimate uncertainty of 150m for deep water and 180m between coastlines and the continental rise for the SRTM15+ dataset. Weatherall et al. (2015) showed in their Figure 6 the percentage of bathymetry changes between GEBCO_2014 and GEBCO_08 (GEBCO 2010 release) grids in the North Sea region with differences of over 5% or even 10% in many places. Therefore, the bathymetry uncertainty in this study is defined as 5%.

The Chezy coefficients of bottom friction are often empirically defined. A typical Chezy coefficient value is 62.5 $m^{1/2}s^{-1}$. The Chezy constants vary because of the ocean bed topography. For example, a higher value of coefficient is expected in the region with ocean mountain bathymetry. We use the value of 20% as the uncertainty of Chezy coefficient. The 20% changes of bottom friction coefficient is comparable to the 5% changes of bathymetry.

We have added the explanation into the Section 4.1.1 Experiment Design of the paper:

“Bathymetry uncertainty is defined as 5% from the knowledge that only a fraction of the ocean seabed has been surveyed, and the remaining errors are significant (Tozer et al., 2019). We empirically defined the uncertainty by investigating its varying range.”

- On p. 18 line 357-359: There were twice “It is observed that in the Arctic Ocean, the initial RMSE with the value of 11.03cm is larger than other regions.”. Remove one.

Response: We have corrected it.