Replies to comments on manuscript #ESSD-2025-404 titled "The DTU25 Mean Sea Surface: From and For SWOT"

Bjarke Nilsson[1], Ole B. Andersen[1], and Per Knudsen[1]

[1]DTU Space, Technical University of Denmark, Kgs. Lyngby, Denmark

June 26, 2026
Under review at Earth System Science Data

Response to the editor:

We thank the editor and the anonymous reviewers for their constructive comments and suggestions. We have addressed them in our revised manuscript and marked changes and responses with blue.

Best regards,
Bjarke Nilsson, Ole Andersen and Per Knudsen

Response to reviews

Overall answer: We appreciate the comments of the anonymous reviewers and have addressed each comment with the associated changes made to the manuscript.
Additionally, we found a few typos that have been corrected, which includes equation (2).

Reviewer 1

The manuscript proposed by Nilsson et al. aims providing a new Mean Sea Surface from satellite altimetry including features from recent observations of the wide-swath altimeter SWOT. Depending considered wavelengths, the use of SWOT altimetry allows improving Mean Sea Surface at intermediate and short wavelengths including coastal regions.

The manuscript is detailed, clearly explained and all limitations of the product are explicitly discussed. Even if the product will most probably evolve with improvements in SWOT processing and the increasing length of observed time series, the provided dataset is an important step in the Mean Sea Surface estimation.

Specific comments

- **[R1/1]** Figures are particularly well designed. However, following ESSD publishing recommendations, it would be important to double check with provided tools to improve the accessibility of colour figures (`https://www.earth-system-science-data.net/submission.html#figurestables`) mainly for uncertainties.

  Answer: Thank you for this recommendation, as we want to make sure that the figures are discernible for everyone. We have changed the colormap for the uncertainty figures, as asked in another comment. Additionally, the red-green colors in figure 16c has been changed in order to make it easier to discern. The turbo colormap has been used quite extensively for large-range figures, which we chose as it has been recommended over older colormaps such as jet or rainbow.

Minor and technical corrections

- **[R1/2]** Figure 4
  As for figures 2 and 3, it would improve the readability to see the location where are show the coastal comparisons.

  Answer: We agree with the suggestion and have added this to the figure. We choose this area as it is the same area as in Fig. 10, however as this one comes first, we have agreed to add the context map.

- **[R1/3]** Figure 8
  The chosen colormaps are not perceptually uniform. It could make sense for MSS to track large features but I would suggest to use a perceptually uniform colomap for uncertainties.

  Answer: Thank you for the suggestion. We have changed it to be the "viridis" colormap, however we had to change the maps range in order to show the small scale details of the oceanographic variability we wanted to show with the original map.

- **[R1/4]** Figure 14
  Please revise the figure caption to improve readability as several a,b,c appears on the figures and are not described in the caption.

  Answer: Thank you for the comment, we agree that the original figure was not easily enough to understand. We have changed the labeling, and added a connecting line between the relevant figures in order to highlight the plots that are connected.

- **[R1/5]** p.6 / l. 127 – please replace “The parameters is” by “The parameter is”

  Answer: Thank you, it has been corrected

- **[R1/6]** p.14 / l. 276 – please corrct “latitudional” by “latitudinal” or “meridional”

  Answer: Thank you for the catch, it has been changed to "latitudinal"

Reviewer 2

- **[R2/1]** The study has modeled a MSS in different frequency bands, including long wave (>20km), intermedium wave (4-20km), and short wave (<40 km from coasts). How to define the long wave (>20km), intermedium wave (4-20km), and short wave (<40 km from coasts) of MSS? The scale around 20km in oceanography should be sub-mesoscale.

  Answer: Thank you for the comment, as this is quite a central and important part of the construction of the MSS. We notice that the characterization (our wording we used for each of the stages) would not be the best in describing the actual contents of each step (the ones illustrated in figure 1). Additionally here we on purpose made the spans overlap and the borders fuzzy. Additionally, the benefit of using SWOT 250m product in the coastal zone is primarily because of the ability to get closer to the coast, and not necessarily because of the ability to capture the smaller wavelengths than for SWOT 2 km.

  In order to improve the characterization we have corrected the section titles, and the describing text, as well as the illustration we have in figure 1. The explicit mention of the wavelengths from the section titles have been removed, as the illustration shows that they are overlapping. The names of the stages have been changed to:

  Section 1: Long wavelengths

  Section 2: Short wavelengths

  Section 3: Coastal zone

  Relating the questions about the definition of the scales, we defined the scales according to the wavelength capable of being resolved with the conventional nadir altimetry, which is roughly 20 km, and what is introduced from wide-swath altimetry with SWOT. The upper limit of approximately 50 km therefore stems from the correction we apply on SWOT to reduce the effect of the dynamic ocean signal. The lower limit is then constrained by the lowpass filter applied on the 2km ocean SWOT product. In order to show these classifications we have extended the paragraph about the staging process in the paper.

- **[R2/2]** Multiple sources of satellite altimeter data were used in the manuscript. Detailed information on all satellite altimetry data used should be provided. How to unify the spatiotemporal datum of different altimetry data?

  Answer: We agree with your proposal and have added the information about all the satellites used to construct the MSS. The initial thought was that the focus should be on the new approach, which was the inclusion of SWOT, whereas the satellites and methodology for the long wavelength MSS is almost identical to the DTU21MSS, which is why we referred to this and has this section be quite short.

  However to make it more clear for the reader how the whole process is carried out, and making the paper more independent, we have extended this section of the paper. Additionally, we found that Jason-3 had been mentioned erroneously as having been included in the reference orbit, which has been corrected. We thank the reviewer for this note which helped find this.

  In regards to the unification of the datum of the different altimetry data, we had not explicitly stated this as we kept the focus on how we made SWOT forced to the reference period used for the MSS. In regards to the conventional altimeters, the process is the same as for the suite of DTU models (DTU21MSS and older), which is why we had the reference but did not go into details. However we have added a description of this into the paper. Additionally we extended the references to older MSS models here.

- **[R2/3]** Is the MSS model constructed using 20 years of satellite altimeter data?

  Answer: It has been constructed using a time-span of more than 20 years, along with the additional 1.75 years from SWOT. However the very large scale (scale of the size of the orbital gaps in the reference orbits) are constrained by the 20 years of the TOPEX/Poseidon, Jason-1 and Jason-2 tracks, which is what constrains the t_0 to 1. January 2003, as other altimeters, including other ERM missions, are fitted down to the surface spanned by the TOPEX/Poseidon, Jason-1 and Jason-2 tracks. The time-spans of the missions have been added in the new table (table 1), which includes the included satellite data as well as the span for each.

- **[R2/4]** The MSS in Eq. (1) corresponds to t0. But t0 is 2003, why? t0 should be the middle time of the data period.

  Answer: The t0 is the center of the first-stage of the MSS construction by using 20 years of TOPEX/Poseidon, Jason-1 and Jason-2 data, with a start from 1993 and end in end of 2012, which corresponds to a central time of 2003. This was not clearly written before, which is why it has been explicitly written in the text now, as well as described in the added table.

- **[R2/5]** There are a large number of data gaps in the SWOT/KaRin altimetry data for one cycle. How to handle these data gaps?

Answer: We stack 31 cycles of SWOT, which was available at the time of writing, which significantly limits the amount of locations with gaps. Nonetheless, the correlation length defined when doing the Least-Squares Collocation ensures that if we have occasional gaps, the interpolation between points follows the assumed correlation function, or if the gap is too large, converges back to the reference surface which in this case is DTU25_LW, and includes the reference altimetry. This is the exact same case for the question on how we handle the data-gaps in Figure 8. A mention of this convergence was added in this section as well, to help the reader interpret the behavior in gaps.

- **[R2/6]** The signal-to-noise ratio of the 250m SWOT/KaRin altimetry data is very low. How to improve the quality of these data?

  Answer: We appreciate this question as it is something that is very important when utilizing the 250m SWOT data. A few things have been done exclusively on the 250m data in order to make it coherent with the 2km SWOT data:

  We scale the point wise uncertainty with 4, to resemble the larger noise-level in the data. The scale of 4 is determined from the fact that the 250m data is oversampled with a factor of 2, so the actual data-resolution is closer to 500m. This leads to the scale which is described in equation 16.

  Another effect is the fact that we use the same correlation length for the 250m data and for the 2km data. This is due to the geodetic signal we want to incorporate into the MSS model is assumed to be the same length no matter the if the data itself is given at 250m or 2km resolution. This smooths the data, but makes sure that we can get closer to the coast, as we do the Least-Squares Collocation only on the good data and with higher noise associated with each datapoint. This has been added to the uncertainty modelling section (section 2.4) in order to make this more explicit.

  Future data versions of the SWOT 250m data product is assumed to be better, which is also something that we have added in the section 5 "Current Limitations and Future Outlook", as this is something that would need to be included in future versions of the MSS.

- **[R2/7]** The SWOT/KaRin altimetry data has a relatively short time. What corrections have been made to the short-term SWOT/KaRin altimeter data in order to obtain data that is consistent with the observation time required for MSS modeling?

  Answer: This is a good question, as this is one of the main influences on the incorporation of SWOT into a MSS. We preprocess the SWOT data before the gridding by doing the corrections described in section 2.2.2. We do a long wavelength parametric correction to each SWOT pass, where we determine the correction based on the residuals between SWOT and the reference surface DTU25$_{LW}$ MSS, which is fixed to 2003. This is illustrated in figure 2, which shows how we get the small scale anomalies that are gridded and then added back to create the DTU25MSS with the remove-restore process.

  This is similar to the process used to include the geodetic missions (GM) in earlier MSS models, such as the DTU21MSS. The difference being here that the corrections for the older GM missions was done on a nadir profile track, whereas for SWOT this is done as a plane due to the 2D geometry of the data.

  This correction makes sure that the data is consistent with the time epoch of the other MSS models as seen with the examples in figure 3, which shows the influence of using different strengths of corrections.

- **[R2/8]** Why is the PSD of DTM25 the smallest in the high-frequency part in Figure 7 (c)?

  Answer: The spectral properties of all the MSS included in Figure 7c at wavelengths shorter than 10 km and especially below 5 km are all a result of the individual MSS smoothing and/or gridding strategies. Different power levels in this range should therefore not be taken as measure of improvement, which is why we did the coherence analysis in Figure 15, to determine to which wavelength the fields carry information. This was stated in the section as "The small wavelengths below 10 km primarily resembles the gridding or smoothing strategies utilized by the different methodologies.".

  The increased power of the Hybrid model in the shorter than 5 km waveband is assumed to be from the high frequency effect of stitching different MSS fields together [1]. This has been added to the text as "The increase in power at the shortest wavelengths could be a result of the stitching of different MSS in the HybridMSS, however this has not been further studied [1]". The low power level for the DTU25MSS at these short wavelengths are a result of the covariance function used for the gridding, making a smooth grid at wavelengths 10 to 5 km.

- **[R2/9]** How are the data gaps handled in Figure 8?

  Answer: As we saw in regards to the case where we have gaps in the SWOT data, if we have gaps that are longer than the correlation length, the gridded anomalies converges to zero. With an anomaly value of zero, when we add back the reference surface, we are left with the reference surface in the gaps. This is one of the reasons we still include the Geodetic Missions in the reference surface, as we would be lacking the high resolution data in the gaps.

We noticed that this is an important effect of utilizing the Least-Squares Collocation, but that we had not explicitly mentioned this in the section where we mention the gaps, so we have now added a mention of this in section 3.1: "In areas with no SWOT data, such as these gaps, the MSS converges to the reference MSS, which in this case is the DTU25$_{LW}$MSS.". Thank you for this indication.

- **[R2/10]** What corrections are made to Sentinel-3 altimeterry data in Table 1? How to define short wavelength?

  Answer: The Sentinel-3A&B altimetry utilized are from RADS, which is fully corrected and referenced to the ellipsoid (so the full SSH), before we use different MSS models. We acknowledge that we had not explicitly stated this in the text, so we have added the sentence and reference: "The Sentinel-3A&B data utilizes the full corrections from the Radar Altimeter Database System (RADS), but referenced against the ellipsoid in order to use our different MSS models for testing [2]."

  The wavelength was chosen in order to match the spatial scale where we actually utilized SWOT, which was dominated by other differences caused by the different epoch with which the Sentinel-3 stacks and the MSS are referenced (both the DTU models as well as the CNES-CLS models). We see that this was not very well described in the text, so the text has been changed to:

  "To see the effect of utilizing SWOT, which is generally smaller than the difference in mesoscale contents in Sentinel-3A&B and the MSS models (See figure 13a), we also high-pass filter the Sentinel-3A&B passes before computing the statistics. The high-pass filter used is a Savitzky-Golay filter, which is a moving window polynomial fit, which better preserves amplitudes of the signal [3]. We use a second order filter with a window length of 50 km to better match the spatial scale where we have utilized SWOT data (see figure 3). "

- **[R2/11]** Why is the PSD of DTM25 the smallest in the high-frequency part in Figure 15?

  Answer: This is the same reason as for Figure 7, and why we do the analysis in figure 15d and 15f, as we see that even though there are a difference in power level this is an artifact of the smoothing and gridding strategies used in the creation of the MSS models. This has been made more explicit in the reference to the earlier figure, by adding:

  "For the PSD one can visually see how the spectra of the different MSS models compare with the power level of the SWOT stacks. The plot here resembles the one from figure 7c where we saw that it is not possible to distinguish between appropriate filtering and thereby matching the power level of SWOT, or actually containing signal within this power signal. "

References

[1] A. Laloue et al., “Merging recent mean sea surface into a 2023 hybrid model (from scripps, dtu, cls, and cnes),” en, *Earth and Space Science*, vol. 12, no. 2, e2024EA003836, Feb. 2025, ISSN: 2333-5084, 2333-5084. DOI: 10.1029/2024EA003836.

[2] R. Scharroo, E. Leuliette, J. Lillibridge, D. Byrne, M. Naeije, and G. Mitchum, “Rads: Consistent multi-mission products,” en, in *Proc. of the Symposium on 20 Years of Progress in Radar Altimetry*, Venice, Italy: European Space Agency Special Publication, Sep. 2012, ISBN: 978-92-9221-274-2.

[3] A. Savitzky and M. J. E. Golay, “Smoothing and differentiation of data by simplified least squares procedures.,” en, *Analytical Chemistry*, vol. 36, no. 8, pp. 1627–1639, Jul. 1964, ISSN: 0003-2700, 1520-6882. DOI: 10.1021/ac60214a047.