Responses to comments of Anonymous Referee #2

Below we present the reviewer's comments in black, while our responses are in blue and directly follow each comment.

General comments

This is the second submission of the paper "Improving the SST in a regional ocean model through refined SST Assimilation". As before, the manuscript describes a new system to assimilate passive microwave data into a regional model near Norway. The bias correction system for these data and a new observation operator (the supermod operator) are described. The authors claim improved results from these new systems giving statistics from a run coving April-June 2018. A spectral analysis is also presented.

The authors have done a lot of work since the first revision of the paper, and it is now much improved; I thank them for their efforts. However, the description of the effect of the supermod operator is, in my opinion, still incomplete. Specifically, from the results given, it is impossible to separate the impacts of the thinning from the supermod operator itself. As the supermod operator is one of the major developments described in the paper, it is important that its effects are seen in isolation. The obvious solution to this lack would be to present full results from an experiment with thinning, but without the supermod operator applied. Panel c in Fig 7 shows the mean increments from such an experiment, but this is a very cursory inclusion as no statistics or other analysis is presented. Instead, a 'thinning only' experiment should be given the same prominence as was given to the other experiments so a reader can see how it differs from the experiment including the supermod operator.

Due to the lack of results from a thinning only experiment, I am not yet willing to accept the paper and instead think it needs further revision. This is a shame as otherwise the paper is of a high quality needing only very minor changes

Please note that what I am asking for is more than 'minor', which means I am forced to put it down for 'major revision' again (it's the only higher option other than reject). However, I do think the paper is in a much better state than this somewhat harsh description implies.

A detailed list of my comments about the paper can be found in the attached PDF.

First of all, we want to thank you for the feedback. Your comments are very helpful in improving the manuscript.

We have addressed your suggestions and added an additional experiment where a thinned set of the PMW SSTs is assimilated without the supermod operator applied. This experiment is called PMW1-thinned, and we introduce it together with the other experiments in Table 2 (in manuscript). The SST RMSE and bias have been calculated for this experiment, and the results are added to Table 3 (in manuscript). As discussed in the manuscript, only thinning the observations is insufficient to spread the increments over the actual observation footprints (as illustrated in Fig. 7c in manuscript). Moreover, the error statistics demonstrate that PMW1-thinned validates worse than PMW1 and PMW2 both when validating against SSTs from satellites and drifting buoys (Table 3 in manuscript). This indicates that the information provided by the observations is used more efficiently when the footprint operator is applied.

There is also an additional problem with PMW1-thinned. This experiment assimilates the thinned PMW SSTs as point observations, and there is a substantial spatial distance between each observation being assimilated at the same time step. This results in a background with an elevated level of noise in the surface temperature fields. The creation of such noise is prevented in PMW1 by adjacent observations with supporting information of the 2D-field (the resolution of the AMSR2 product is 25 km x 25 km, while the footprint of the sensor is ~35 km x 62 km, thus neighboring observations (and their corresponding errors) are correlated). In PMW2, the supermod operator prevents the creation of such noise. An example of the increased noise in PMW1-thinned is illustrated in Fig. 1 for a single analysis cycle. The increments at the last time step are clearly not spread over the footprint size (Fig. 1, upper panel). This results in a background with visible "blobs" in the SST field at the observation locations (Fig. 1, lower panel). As these “blobs” of either cooler or warmer water than the surroundings propagate with the flow, smaller-scale structures, which in reality are unwanted noise, are generated. The most apparent approach to reduce this problem would be to increase the observation error. However, as the error statistics calculated from PMW1-thinned are worse than those from all other experiments (except the free model run), it is unlikely that a reduction of the assigned observation error would yield improved validation statistics.

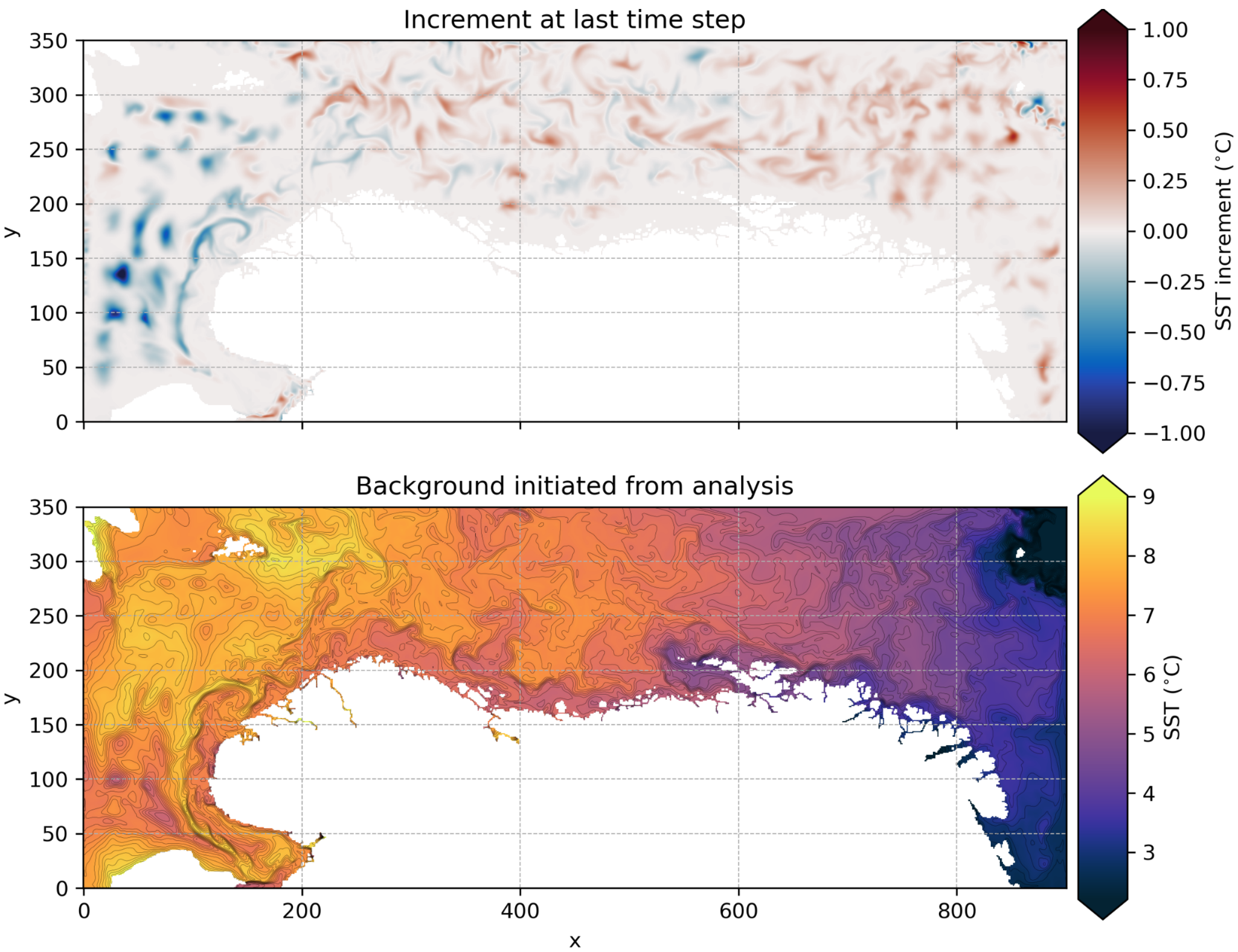

Figure 1: Increments at the last time step of the analysis cycle covering 28 – 30 April 2018 (upper panel). First time step of the background initiated from the analysis created during the cycle covering 28 – 30 April 2018 (lower panel). Both the increments and the background are from PMW1-thinned.

Specific comments

P4, L92:

"The latter is connected to errors arising from the pre-processing and quality control of the observations, the observation operator, and the mismatch between the resolutions of the observations and the model grid."

I don't agree with this sentence. measurment errors are the errors in 'y' (the observations), including all the preprocessing and QC. Representation errors are the errors due to the application of the observation operator to the model (i.e., H(x)), which are mainly due to the mismatch in resolutions

We used the definition of measurement error and representation error as presented in Janjić et al. (2018). This paper presents a thorough review of the representation error in geophysical data assimilation and attempts to consolidate the terminology used within the field of geophysical data assimilation. The paper has been widely cited in the literature since its publication. According to the definitions presented in this review paper, the measurement error is related to only the instrument, while the representation error includes errors due to unresolved scales and processes, errors arising from the pre-processing, and the observation operator itself. We would like to remain true to this definition and thus choose to keep the sentence, only with a minor change to clarify that these definitions are from Janjić et al. (2018):

Following Janjić et al. (2018), *the latter is connected to errors arising from the pre-processing and quality control of the observations, the observation operator, and the mismatch between the resolutions of the observations and the model grid.*

Fig 3:
I assume this is the number of observations per day. Please update the figure so that this is stated clearly.

Yes, it is the number of observations per day. We added “per day” in the figure caption:

Time series of the number of observations ***per day*** *available inside the model domain for each sensor and satellite pair and for the CORA drifting buoys.*

P10, L220: Please state how is the weight is calculated. Presumably it's based on the fractional area, but I think you need to explicitly state this.

We have now added a sentence to state that the weights are based on the fractional area:

As the center of the observation footprint may be located between model grid points, the supermod value is calculated as a weighted mean of the values in grid cells that fall completely or partially within the footprint area. ***The assigned interpolation weights are based on the fractional area of the grid cells that fall within the footprint.***

P11, 237: “*similar*”.

You specify the error standard deviation yourself, so you should tell the reader explicitly what it's value is. Also state your justifications for using that value. Saying it's 'similar' to the background error is vague. Also it makes me wonder why it isn't the same as the background error. However, the figure claims that the values are the 'same', which contradicts what you are saying here (but is what I would actually expect).

The value of the observation error is indeed equal to the background error. We have changed this in the text.

P12, L248: *“In the extreme cases of a very small observation error, the increment might increase with increasing L.”*

I'm not asking for additional tests, but please state that you either: 1) Explicitly observed larger increments when the observation error standard deviation was small. 2) Speculate that larger increments are possible, but that they weren't observed within the range of parameter values tested.

We did, through an idealized test, observe larger increments when the observation error was set much higher than the background error. To clarify that this is what we mean we have rewritten the sentences:

Further tests within this idealized framework revealed that the amplitude reduction with increasing L is not as pronounced when the observation error is set much smaller than the background error. In cases where the observation error is very small compared to the background error, the amplitude of the increment starts to increase with increasing L.

P14, L285: *"This larger bias does not reflect the ability of the PMW SST data set to adjust the model. Rather, we find the bias to be a result of having no PMW observations in coastal zones, causing also the parts of the coastal current that extend beyond these zones to be too cold during its heating phase as summer approaches".*

I suggest you reword this. It reads as if the statistics in the coastal zones are degrading the results. However, this contradicts your earlier sentence were you state that you exclude the coastal zones from the statistics. What I think you mean is that the extension of the coastal current into the statistics zone is degrading the results, but I don't think this is sufficiently clear.

You are right, that is what we mean. We have rewritten this part:

When validating against IR SSTs, PMW1 has a larger bias than IR2. Upon inspection of the spatial distribution of the model minus observation differences that contribute to this elevated bias value, it is clear that the elevated bias is mainly caused by elevated errors in regions where the coastal current extends into the parts of the model domain that are considered in the validation. Thus, this larger bias does not reflect the ability of the PMW SST data to adjust the model. Rather, the elevated bias values are caused by advection of cold coastal water, which is unconstrained by PMW SSTs, into the region used for calculating validation statistics.

P15, L300: *"Also, a circular structure in the increments can be seen just north of 69N".*

It's not sufficiently clear what you are referring too. There are two features in panel (a) north of 69N that could be described as vaguely 'circular' - a largish positive increment, and a region of low increments just off the coast. I think you mean the positive whirl of red, but please word so that this is unambiguous.

Yes, that is what we mean. We have changed the sentence to:

Also, a large positive whirl in the increments can be seen just north of 69N in both panels.

P15, L306: *"close to the coast around 63N".*

The increments near the boundary at 66N are just as large as this and are not present in PMW2, but you don't mention them.

You are right. We added these increments to the list:

*(north of 72N, **close to the western boundary at 66N,** and close to the coast around 63N)*

P15, L310:
What are the statistics for the experiment, with thinning but without the supermod operator. Myself and other readers would likely be interested to see such results. In my opinion this experiment should be treated as a third PMW experiment (PMW3) and validated in a similar way to the other experiments. The fact that this does not seem to have been done, is a significant deficiency of the manuscript. If these results had been included I would have suggested only minor technical corrections for the paper. But, as it stands, I feel unable to do so.

We have now added these statistics. See our answer to the general comments.

P17, Eq. 3: Please call this the "radial wavenumber" to distinguish it from 'm' and 'n' which are also wavenumbers.

That is true. We changed it to “normalized radial wavenumber”.

P18, L372: *“distributed”.*

I assume that you calculate the mean of all the bins that fall within the wavebands. But please state this.

The elements in the variance array that fall into a wavelength bin are added, and we do not calculate the mean. This is the same procedure as in Denis et al. (2002). To clarify, we modified the sentence to:

To create a one-dimensional SST power spectrum, all individual spectral variance elements, $\sigma^2(m, n)$, that fall within a given wavelength bin λ are summed in order to find the total variance in this bin.

P19, L82:. *“Assimilating PMW SSTs without using the supermod operator thus has a smoothing effect on the modeled SST, indicating that the average effect of the high level of detail seen in the increments is a removal or smoothing of structures present in the background state.”*

From the results presented it is not possible to know if it is the supermod operator, the thinning, or both, that has had the coarsening effect. This is why full results with thinning, but without the supermod operator should be given.

Assimilating the PMW SSTs as point observations, which we did in experiment PMW1, results in smoother SST structures. When we thin the observations and use the supermod operator, which we did in PMW2, this smoothing is prevented. Thinning the observations and not applying the operator also prevents smoothing. This is within expectations, as the observations are separated by a substantial spatial distance.

However, as mentioned in the answer to the general comments, thinning without applying the supermod operator introduces noise in the SST field. In Fig. 2, we have included the power spectrum for PMW1-thinned, along with the other experiments' power spectra. As PMW1-thinned does not have a coarsening effect, its spectrum is expected to be similar to the spectrum of PMW2. This is the case for the largest scales (>60 km), where the spectra follow each other. However, for smaller scales (<60 km), we find that the two spectra separate: PMW1-thinned has more small-scale structures than PMW2. This can be attributed to the noise that the assimilated observations in PMW1-thinned insert into the modeled SST.

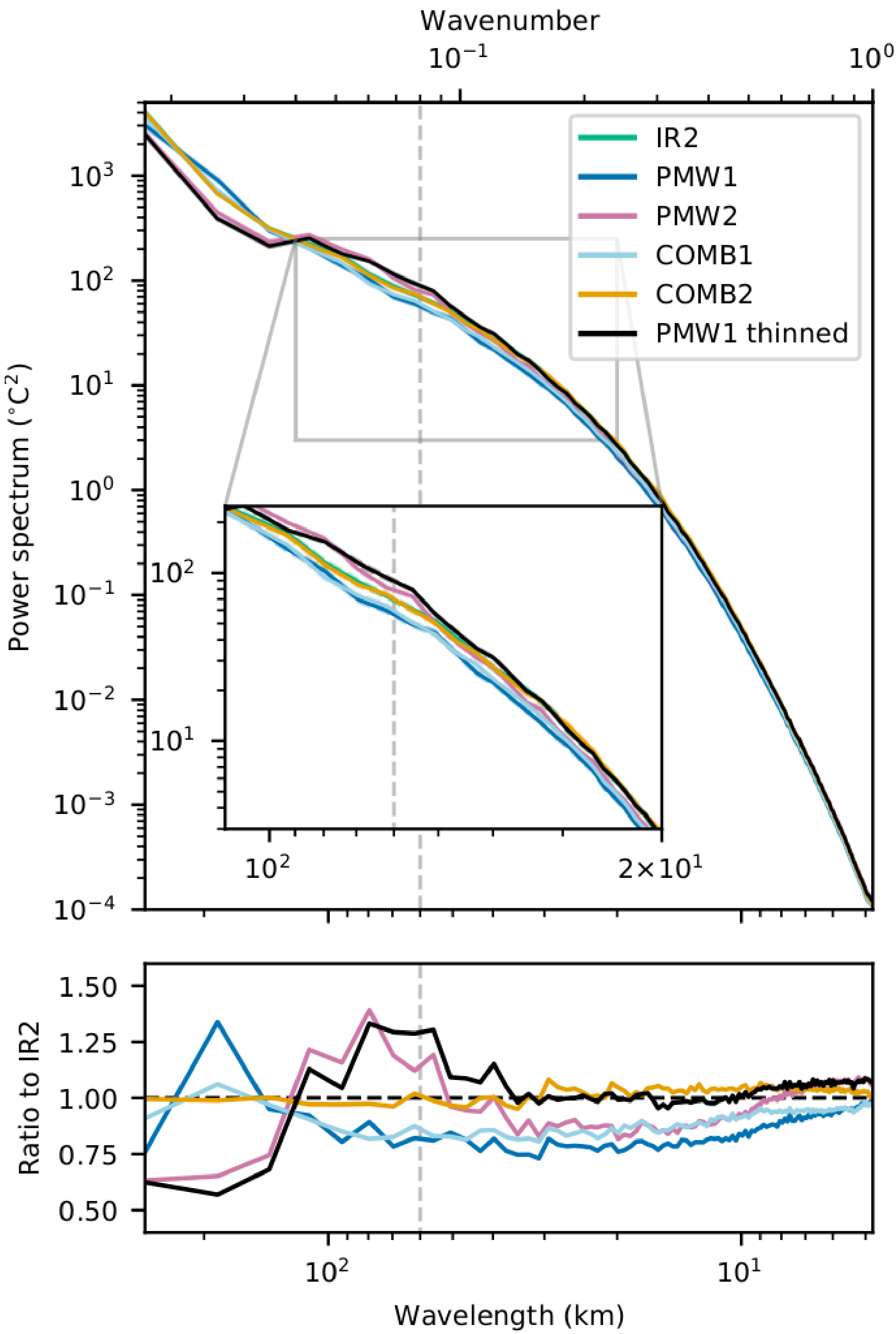

Fig. 2: Same as Fig. 9 in the manuscript, but the power spectrum of PMW1-thinned has been added (black line).

References

Denis, B., Côté, J., and Laprise, R.: Spectral Decomposition of Two-Dimensional Atmospheric Fields on Limited-Area Domains Using the Discrete Cosine Transform (DCT), Mon. Weather Rev., 130, 1812–1829, https://doi.org/10.1175/1520-0493(2002)130<1812:SDOTDA>2.0.CO;2, 2002.

Janjić, T., Bormann, N., Bocquet, M., Carton, J. A., Cohn, S. E., Dance, S. L., Losa, S. N., Nichols, N. K., Potthast, R., Waller, J. A., and Weston, P.: On the representation error in data assimilation, Q. J. Roy. Meteor. Soc., 144, 1257–1278, https://doi.org/10.1002/qj.3130, 2018.

Changes made in the manuscript

One experiment (called PMW1-thinned) has been added to the manuscript. We have also modified the manuscript according to the reviewer's comments.