

Reply to reviewer 1

Major comments have been addressed in the review. I think the paper therefore requires minor revisions. Please see below my general and specific comments.

GENERAL COMMENTS

I would like to again, add as a cautionary note, that comparing “raw” and “gapfilled” values and exploring their difference is not related to the merit of the gap-fill, due to the complex missingness pattern of the soil moisture data. I would discuss this more prominently in Section 4.1 and Section 4.5. The differences between “raw” and “gap filled” are however very interesting, and likely related to the pattern of missing values that is underlying. I find this very interesting to discuss and would encourage you to write a bit more about it in those Sections. In the abstract and the introduction you cite satellite coverage and radio-frequency interference as a mechanism for the missing values in ESA CCI SM. Note however that according to Dorigo et al, 2017, those are not the only one and quite possibly not the major contributors to missing data. In this citation, they also note that snow-covered pixels are removed since the water in the snow is measured by the satellite, not the soil moisture, in these situations. Furthermore, regions with high vegetation cover are set to missing in post processing, since there the signal cannot penetrate through the vegetation and reports, respectively, only the water stored in the above-ground vegetation. I haven’t looked into how those two missingness mechanisms play a role in your study area, but it could be that the snow-cover problem is responsible for many missing values in winter (e.g. Fig 5a) and the overall wetter gap-filled values in high latitude regions in Figure 13 and Figure 5b,c for winter. Or, it could be due to vegetation cover. It might be interesting to investigate, for example by plotting Figure 13 separately for each month, to see where the “wet” signal in the gapfill is coming from and which missingness mechanism it can be explained by, if any. Unfortunately, I still can’t wrap my head around the applied variable correction. I understand now that this is applied to the ERA SM data before using it for the gapfilling. I agree that a bias is very likely to exist between ESA SM and ERA SM and needs to be corrected before using traditional machine learning methods. But I don’t yet understand what the difference between Equations (3) is and standardized anomalies. When I inspect the equations, I understand that the result is the mean of the ESA SM plus the anomalies of the ERA SM, scaled with the ratio of their standard deviations. To me, this is an equal procedure as using standardized anomalies for both ERA SM and ESA SM. However, both is fine, so no need to change the variable correction. However, also note that for the Random Forest method, scaled/standardised variables are not necessary, since the scale of a feature (input variable) does not depend on its importance after training. (E.g see <https://datascience.stackexchange.com/questions/62031/normalize-standardize-in-arandom-forest> <https://stackoverflow.com/questions/8961586/do-i-need-to-normalize-or-scale-data-for-randomforest-r-package>; I could not find a literature source for this unfortunately but it derives logically from the RF

function). So you might do additional work here that is, after all, not necessary, if I understood everything correctly. As far as I understood, the training period of the Random Forest, described in Section 3.2.1, is on the years 2003-2008, and therefore overlaps with the Long term extension, described in Section 4.5., that runs from 2005-2015. Since using the same data for training and predicting with a Random Forest likely leads to overestimation on the merit of the Random Forest, I suggest adding a cautionary note to that effect in the text.

Response: Thanks for your valuable time and constructive comments. We tried our best to incorporate them in the new version. The detailed modifications can be found in the highlighted text throughout the manuscript.

SPECIFIC COMMENTS

1. L12 and L58+59: radio-frequency interference is mentioned as a major reason for gaps in the ESA CCI SM data. However, many values in the ESA CCI SM are also missing because of snow cover, frozen soil, or dense vegetation (Dorigo et al, 2017). Since those mechanisms are relevant for the interpretation of the results (see general comments above), I think they should be included here.

Response: Thanks for pointing out this issue. We have revised this in the new version.

2. L29: missing comma “soil moisture (SM),”

Response: We have revised this in the new version.

3. L39 optionally add Dorigo et al, 2021

Response: We have added this in the new version.

4. L84: sentence a bit unclear. Is “compared” meant instead of “focused”?

Response: Thanks for pointing out this issue. We have deleted this in the new version.

5. L65: Bessenbacher et al, 2022 useful citation here

Response: We have added this in the new version.

6. L65, L197, L357, L523: “strong capacity/capability” leads in my opinion to convoluted sentences and is not very clear. Try to not use as much.

Response: Thanks for pointing out this issue. This has been revised through the manuscript.

7. L67: no brackets needed around citation

Response: We have revised this in the new version.

8. L95: missing space character before Zhang et al

Response: We have revised this in the new version.

9. L128ff: add in brackets behind (i), (ii), (iii) where they can be found in Fig. 2. Example: “(i) use a regression (...) bias between them (Fig2 Part 1 red text);”

Response: Thanks for pointing out this issue. We have revised this in the new version.

10. L186: possible typo “MODSI”

Response: We have revised this in the new version.

11. L207: remove “reliable”

Response: According to the reviewer’s suggestion, this has been revised in the new version.

12. L207: presented -> present

Response: We have revised this in the new version.

13. L240: if available, it would be really interesting to know what the computational efficiency of the presented gap-filling algorithm was, i.e. how long it roughly ran on how many CPUs / which machine. If possible, would be nice to include this information!

Response: In this study, the random forest model for gap-filling SM is implemented in 2 CPU cores. It approximately takes 12 hours in gap-filling 1-year CCI dataset over China.

14. L246: missing space character before citation

Response: We have revised this in the new version.

15. L259: is 2003-2008 the training window or the cross-validation window for the RF parameters? Or both? Please clarify

Response: In our study, the Bayesian optimization process is implemented by using the dataset of 2003—2008 as the cross-validation window. According to the reviewer’s suggestion, we have revised this in the new version.

16. L262: remove “best”

Response: We have revised this in the new version.

17. L291: Do you perhaps mean Eq (1)?

Response: Thanks for pointing out this issue. We have revised this in the new version.

18. L314: is suppose to -> can

Response: We have revised this in the new version.

19. L375-376: severe contamination in winter season is likely related to snow cover in ESA CCI SM, list as reason

Response: We have added this in the new version.

20. L379ff: You state that in the warm season, more missing pixels are reconstructed than in the cold season. You argue this is because surface coupling is larger in summer. This might be true, but how does the algorithm know this? I thought it only leaves gaps unfilled when there are not sufficient neighbouring points available to run the Random Forest. How does this relate to the strength of the surface coupling? Please clarify.

Response: This is only one speculation. Although this has been reported by previous studies, we can not provide direct evidence. According to the reviewer's suggestion, we have revised this in the new version.

21. L382: Yes they tend to produce "bias", however, this is not a problem itself. If the pixels are missing not at random, I would expect bias between "raw" and "gap filled", because the gap filled data might e.g. fill especially pixels under dense vegetation, which are systematically wetter than pixels with less dense vegetation. Therefore, this "bias" is not a bad thing, I would be worried if there wasn't any.

Response: Thanks for the reviewer's suggestion. We have revised this in the new version.

22. L410: consider moving this part of 4.2 into a separate (sub)section.

Response: Thanks for pointing out this issue. We have revised this in the new version.

23. L412: "better" compared to what? As R2 and RMSE are not comparable, because of different units.

Response: Thanks for pointing out this issue. We have revised this in the new version.

24. L419: unnecessary space character after bracket

Response: We have revised this in the new version.

25. L426: “some grids” unclear. Some regions?

Response: We have revised this in the new version.

26. L522: add year 2009 to the table for easy comparison

Response: Thanks for pointing out this issue. We have added this in the new version.

27. L525ff: Add that the gap-filled product is drier overall than the “raw” is consistent with the findings in Figure 5.

Response: According to the reviewer’s suggestion, we have revised this in the new version.

28. L527: “overestimated”: since we don’t know the ground truth of missing values, I would not use words like “overestimated”

Response: We have deleted this in the new version.

29. L531: important finding: trends could be overestimated in satellite SM due to missingness.

Response: Thanks for pointing out this issue. We have added this in the new version.

30. L535f: How does missing values in AOD and missing values in albedo compare to missing values in SM? Since the missing values mechanisms (below clouds) are different from soil moisture (vegetation, snow, interference), why would we expect the effect of gap-filling to be similarly, e.g. reducing trends? This might be related to the next sentence in the text, but unfortunately I don’t understand this sentence. Please clarify.

Response: This merely supports the missing values in satellite data could result in bias of trend. We can not provide one mechanism among difference variables. According to the reviewer’s suggestion, we have removed this to the next paragraph.

31. L549: Unfortunately I don’t understand Figure S7. Is that like Figure14, but disaggregated into trends and seasonal cycle? Then, trends are barely visible and cannot be compared like this.

Response: Thanks for pointing out this issue. In the new version, we have deleted this Figure.

32. L554: “Overall...” unclear statement, please clarify.

Response: We have deleted this in the new version.

33. Figure 14a, b: These values are hard to compare. Idea: combine a and b into 1 plot and mark “raw” and “gap-filled” with different colors. Same for S7

Response: Thanks for the reviewer’s suggestion. In the new version, we have rewritten the Fig. 14.

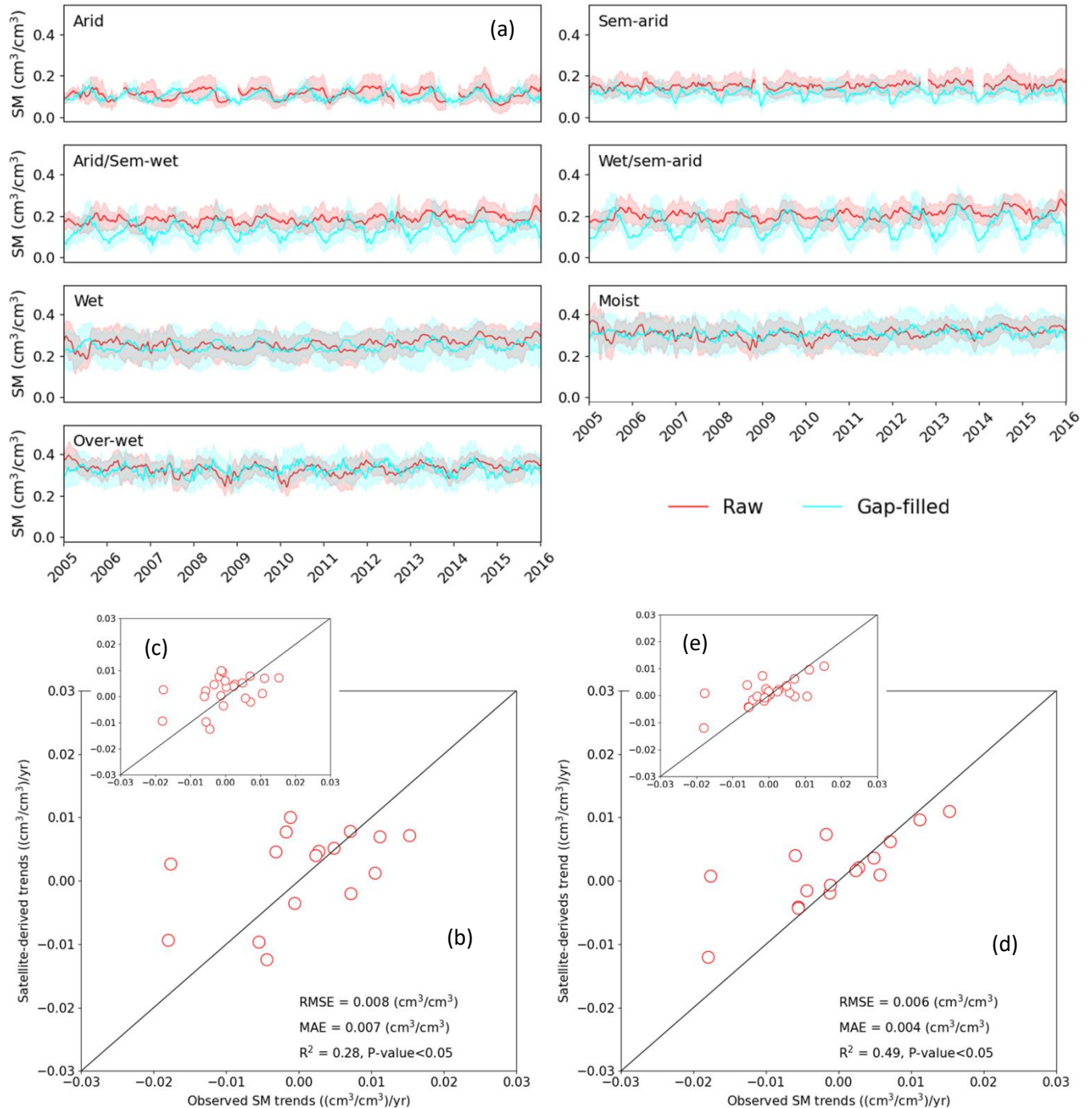


Figure 14: (a) shows the temporal patterns of raw and gap-filled CCI SM regarding different climate regions during 2005-2015. The shaded area in (a) denotes ± 1 standard error. (b) and (c) Scatter plot of 1-km CCI SM-derived trends against in situ measures during 2005-2014, and (b) shows the trends under significance level, while (c) shows all the trends. (d) and (e) Scatter plot of 1-km gap-filled SM-derived trends against in situ measures during 2005-2014, and (d) shows the trends under significance level, while (e) shows all the trends.

REFERENCES

Dorigo et al, 2017: ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions. Remote Sensing of Environment. Volume 203, Pages 185-215, <https://doi.org/10.1016/j.rse.2017.07.001>

Dorigo et al, 2021: The International Soil Moisture Network: serving Earth system science for over a decade. Hydrol. Earth Syst. Sci. 10.5194/hess-25-5749-2021

Bessenbacher et al, 2022: CLIMFILL v0.9: A Framework for Intelligently Gap filling Earth Observations, GMD, <https://doi.org/10.5194/gmd-15-4569-2022>

Reply to reviewer 2

The authors satisfactorily responded to the review comments. My comments are resolved except for Figure 14. I would suggest editing Figure 14 by giving more room to panels (d) and (f). This can be done by having panel c,d in a row and e,f in another row below. Maybe even put (d) through (f) in a different figure. I don't think it's appropriate to have content that cannot be read in 100% zoom level.

Response: Thanks for the reviewer's suggestion. According to the reviewers and editor's suggestion, we have rewritten the Fig. 14 to make it more readable and visible.

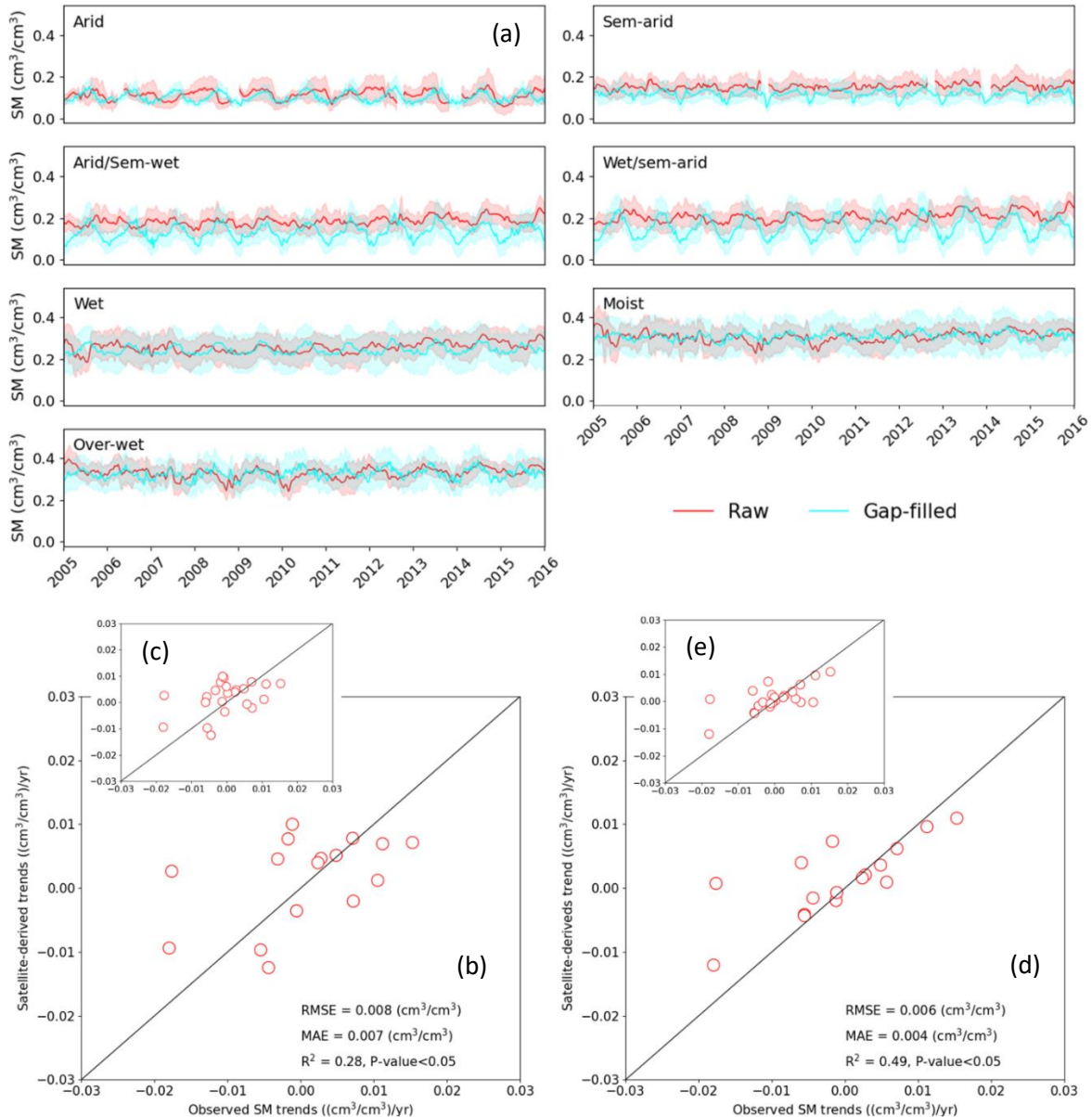


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