

Response to reviewers' comments

Dear Associate Editor:

We have further revised the manuscript in accordance with Reviewer #3's recommendations, which have helped improve its clarity. My co-authors and I sincerely thank the reviewer for the detailed and constructive feedback. Below, we provide our responses to the reviewer's comments. We appreciate your consideration and look forward to your response.

Regards,

Yonghwan Kwon and co-authors

Reviewer #3:

Dear authors,

Thank you for the interesting and extensive paper on multi-sensor soil moisture DA to enhance weather forecasting. The comments of the reviewers during the interactive discussion have been addressed to a large extent. I do have a few remaining detailed comments:

1. The pre-blended soil moisture DA has not been tested for performance comparison in this study. For clarity, I would suggest adding such statement to the Conclusion section where you discuss the merits of multi-sensor over pre-blended DA, e.g. in p56 11053.

Response) In accordance with the reviewer's comment, the paragraph has been revised as follows (Lines 1024–1029 in the revised manuscript).

“... However, a direct comparison of soil moisture DA performance between the two approaches (i.e., joint assimilation of multiple products and assimilation of a pre-blended product) has not been conducted in this study. It is also acknowledged that the overall domain-averaged improvements in atmospheric estimates achieved through multi-sensor soil moisture DA, relative to single-sensor DA, are limited and statistically insignificant.”

2. The analysis of soil moisture DA impact on precipitation forecast skill per region, and variability therein, is nice, and could be an entry point for further analysis in future work. As you already indicate, part of the variability in results per region could be due to seasonality. This could well be the case, in particular because the DA period seems to cover only June and July. Consider adding to recommendations/next research a note on whether it would be worth and feasible to extend the experiment to run for a full calendar year. This would allow for an analysis of the impact of seasonality on the effectiveness of (multi-sensor) soil moisture DA.

Response) We appreciate the reviewer's insightful comment. The following paragraph has been added to the revised manuscript (Lines 839–842).

“The regional variability in precipitation performance between the CTL and soil moisture DA experiments may be attributed to seasonality. A full-year or multi-

year experiment would therefore be valuable in future studies to assess the impact of seasonality on the effectiveness of multi-sensor soil moisture DA for improving precipitation forecasts.”

3. Thank you for reducing substantially the use of abbreviations. Consider leaving out entirely in the Conclusions section the abbreviations for your 4 experiments (or replace throughout the paper the experiment abbreviations for something like 'control' 'ASCAT DA' 'SMAP DA' and 'ASCAT-SMAP DA'.)

Response) The abbreviations for the experiments have been removed from the “Conclusions” in the revised manuscript, as shown below.

*Lines 984–987

[Original] “..., assimilating the ASCAT and SMAP soil moisture retrievals together (MT_ATSP) yields ...”

[Revised] “..., assimilating the ASCAT and SMAP soil moisture retrievals together yields ...”

*Lines 1004–1009

[Original] “... multi-sensor soil moisture DA, relative to CTL, is comparable ...”

[Revised] “... multi-sensor soil moisture DA, relative to the control experiment (without soil moisture DA), is comparable ...”

4. The paper is quite long. Consider shortening where possible. For example in Section 3 introductions of ASCAT and SMAP could be reduced pointing to the references. Also for Sections 2 and 4, consider shortening some of the descriptions and refer the reader to your previous papers.

Response) In accordance with the reviewer’s suggestion, we have shortened Sections 2, 3, and 4 by removing detailed descriptions that are not essential to the main context of the manuscript. In particular, the explanation of the atmospheric DA scheme in KIM (i.e., the hybrid 4DEnVar method) presented in Section 4.1 has been moved to the supplementary material (Text S1), as described below.

“Text S1. KIM hybrid 4DEnVar DA scheme

KIM’s 4DEnVar DA system consists of deterministic and stochastic (ensemble) components whose atmospheric analyses are generated using the KIM VARIational DA (KVAR, Song and Kwon, 2015) and four-dimensional local ensemble transform Kalman filter (LETKF, Shin et al., 2016) schemes, respectively. KIM LETKF independently performs analysis updates by assimilating almost the same atmospheric observations as used in the deterministic component (i.e., KVAR), but the main function of LETKF in the KIM DA system is currently to construct ensemble background error covariance of KVAR (Kwon et al., 2018). The relative contribution of the ensemble background error covariance gradually increases from 45% at the poles to 70% at the equator in the troposphere and then gently decreases

above the troposphere. Three-dimensional spatial localizations are implemented using the Gaspari and Cohn Gaussian-like localization function (Gaspari and Cohn, 1999). To obtain an appropriate ensemble spread in LETKF, an additive inflation (Shin et al., 2018) and relaxation-to-prior perturbation (Whitaker and Hamill, 2012) are applied together.”

5. p2 112: consider "Overall, assimilating single-sensor soil moisture data, ASCAT or SMAP, into.."

Response) The phrase has been revised as recommended (Lines 12–13 in the revised manuscript).

6. p2 120-22: the different wording here may confuse the reader, thinking this reports on yet another experiment. Consider keeping terminology for the experiments consistent. E.g. here it could simply be stated something like: "Also precipitation forecast skill improved with (multi-sensor) soil moisture DA, but not for all regions and events."

Response) Based on the reviewer’s comment, the sentence has been revised as follows (Lines 20–21 in the revised manuscript):

“Precipitation forecast skill also improves with multi-sensor soil moisture DA, although the improvements are not consistent across regions and events.”

7. p3 136: "..the long memory.."

Response) The phrase has been revised as recommended (Line 35 in the revised manuscript).

8. p29 1572-581: consider shortening, just stating the analysis data used, with reference.

Response) In accordance with the reviewer’s comment, we have shortened the paragraph, as shown below (Lines 548–552 in the revised manuscript):

“Evaluations of the specific humidity and air temperature analyses/forecasts are performed using the ECMWF Integrated Forecasting System (IFS) analysis (ECMWF, 2017) as reference data, which has been extensively used for evaluating modeling systems (e.g., Ben Bouallègue et al., 2024; Kwon et al., 2024; Lee et al., 2020; Polichtchouk et al., 2023; Reichle et al., 2023). ...”

9. p30 1606-607: "..skill using well-established metrics, such us.."

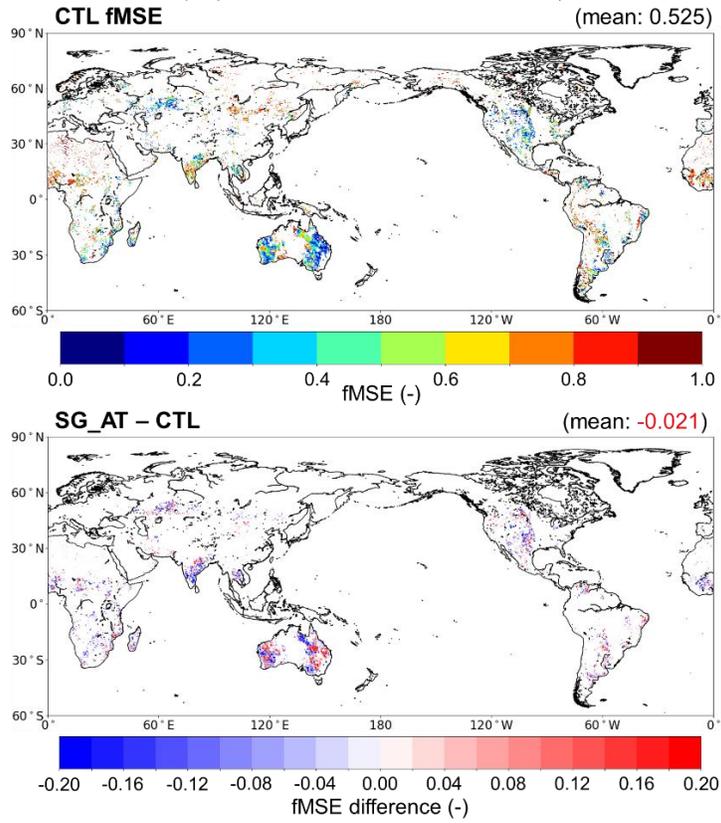
Response) The phrase has been revised as recommended (Lines 576–577 in the revised manuscript).

10. p34 Figure2: consider organising panels vertically in one column to make the maps bigger for readability.

Response) The panels have been rearranged vertically as recommended, and the figure caption has been revised accordingly (Lines 639–646 in the revised manuscript). The revised figure and caption are provided below.

a) Evaluation of ASCAT SM DA

(Triplet: model, AMSR2, and SMOS)



b) Evaluation of SMAP SM DA

(Triplet: model, AMSR2, and ASCAT)

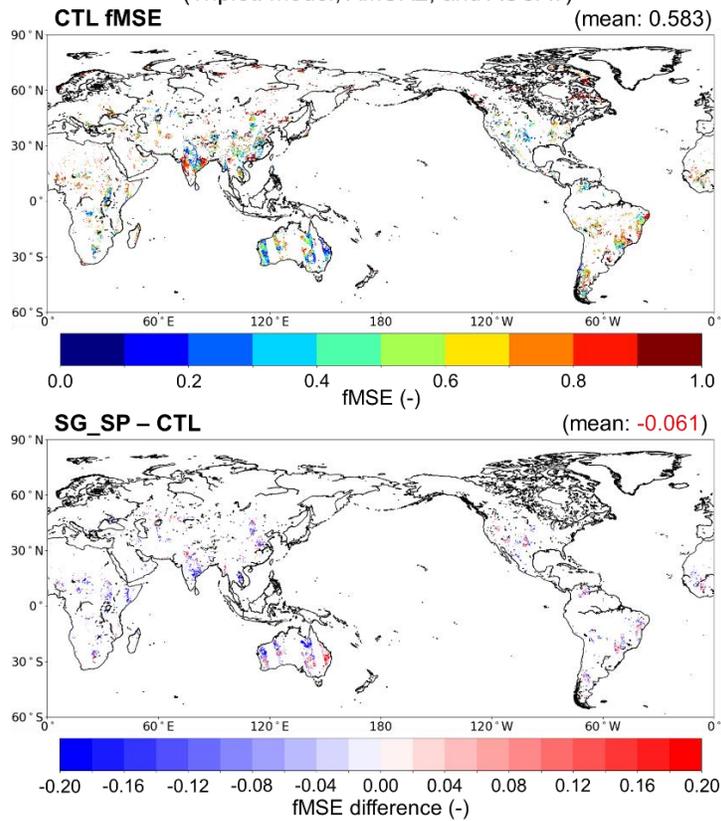


Figure 2. Global maps of the soil moisture triple collocation analysis (TCA) results for (a) ASCAT (i.e., SG_AT) and (b) SMAP soil moisture data assimilation (i.e., SG_SP). In each panel, the top subpanel shows the fractional mean-square error (fMSE) of CTL soil moisture at 04:00 am/pm local solar time (LST) in (a) and 11:00 am/pm LST in (b). The bottom subpanel shows the soil moisture fMSE difference between SG_AT and CTL in (a) and between SG_SP and CTL in (b). Negative fMSE differences indicate improved soil moisture estimates from ASCAT and SMAP data assimilation, respectively.

11. p43 Figure 6: maps are too small to be readable

Response) Figure 6 has been placed on a separate landscape-oriented page to improve readability (Page 44 in the revised manuscript).

12. p53 1985: consider instead of "we aim" something like "The objective was to.."

Response) Following the reviewer's suggestion, the sentence has been revised as follows (Lines 955–959 in the revised manuscript):

“The primary objective is to investigate the impact of simultaneously ...”

13. p53 1990: "..assimilated individually (single-sensor DA) and jointly (multi-sensor DA) into.."

Response) The phrase has been revised as recommended (Line 960 in the revised manuscript).

14. p53 1993: "..EnKF, while.."

Response) The phrase has been revised as recommended (Line 963 in the revised manuscript).

15. p53 1998: "..data, results in.." and "..soil moisture analysis performance of.."

Response) In accordance with the reviewer's suggestion, the sentence has been revised as shown below. However, we retained the phrase "... data results in ..." without adding a comma (Lines 967–970 in the revised manuscript).

“TCA-based evaluations indicate that assimilating either ASCAT or SMAP soil moisture data results in an overall positive effect on the global soil moisture analysis performance of the Noah LSM, with global mean performance improvements of 4.0% and 10.5%, respectively.”

16. p53 11000: "..(i.e. ASCAT and SMAP).."

Response) The phrase has been revised as recommended (Line 970 in the revised manuscript).

17. p54 11014: "..with single-sensor SMAP DA and ASCAT DA.."

Response) The phrase has been revised as recommended (Line 984 in the revised manuscript).

18. p54 11016: "..balanced performance enhancements.."

Response) The phrase has been revised as recommended (Line 986 in the revised manuscript).

19. p54/p55 11022-1028: this may be confusing for the reader. I would suggest to reformulate and simply state the soil moisture DA findings of your experiments for precipitation forecast skill. "The results for precipitation forecast skill show that.."

Response) We appreciate the reviewer's comment. Accordingly, the paragraph has been revised as follows (Lines 993–998 in the revised manuscript):

"Our experiments demonstrate that, within a land-atmosphere coupled system, soil moisture DA enhances precipitation forecast skill through land–atmosphere interaction processes, particularly when multiple soil moisture products from diverse sources are jointly assimilated. Specifically, multi-sensor soil moisture DA improves the prediction of precipitation events, as evaluated using the ETS metric, across a range of precipitation intensity thresholds."

20. p55 11033: "..regional skill improvements.."

Response) The phrase has been revised as recommended (Line 1003 in the revised manuscript).

21. p55 11046: "..is the impact on weather forecast skill of joint assimilation of .."

Response) We appreciate the reviewer's comment. However, we have revised the sentence differently, as shown below (Lines 1016–1018 in the revised manuscript).

"To conclude, a key aspect of this study is the joint assimilation of individual radar- and radiometer-based soil moisture products (multi-sensor DA) within a land-atmosphere coupled system to improve weather forecast skill."

22. p55 11047: "..soil moisture products (multi-sensor DA)."

Response) The phrase has been revised as recommended (Line 1017 in the revised manuscript).

23. p56 11055: start new paragraph with "The following issues.."

Response) Following the reviewer's suggestion, we have revised the text to begin a new paragraph with "The following issues ..." (Line 1030 in the revised manuscript).

24. p56 11059: delete "Lastly"

Response) We have replaced “Lastly” with “Third” (Line 1034 in the revised manuscript).

25. p56 11061: "Lastly, as discussed.."

Response) As recommended by the reviewer, we have replaced “In addition” with “Lastly” (Line 1036 in the revised manuscript).