RC1: 'Comment on egusphere-2025-2124', Anonymous Referee #1

This manuscript develops and presents a novel multivariate data assimilation framework and implements it in an integrated hydrology model. This approach is tested in a catchment in Germany using groundwater and soil moisture observations. It is interesting that this approach resulted in improved state variables and also in some minor improvement to related fluxes such as ET.

Response: Thanks for the cogent summary of our work.

The manuscript is clearly written and organized. I recommend this manuscript be published pending some minor revisions and / or responses to my comments below.

Response: Thanks for your positive feedback.

1. Are (or how are) the _PAR runs spun up to account for potential impact of the parameters (e.g. ln(Ksat)) on model equilibrium states? The methods section does a nice job describing this process in general and it appears that great care was taken here to ensure a good model spin up, but it is still a bit unclear how this interacted with the adjustment of model inputs for these cases.

Response: We appreciate the reviewer's attention to the spin-up procedure. The concern about the interaction between parameter updates in the _PAR experiments and the model equilibrium state is indeed important. In our setup, all experiments were initialized from the same carefully spun-up model state. For the _PAR runs, the saturated hydraulic conductivity (log K_s) was updated every seven days using a damping factor of 0.1, ensuring that parameter changes were gradual and did not disturb so much the equilibrium state, thereby avoiding the need for additional spin-ups. In addition, we validated the stability of the updated parameters by applying K_s values obtained from one year (e.g., 2016) in open loop simulations of other years (2017-2018), confirming that no spin-up-related issues were introduced. To clarify this point further, we have revised the Section 3.2 (Configuration of Data Assimilation Experiments) as follows (lines 362-368):

"For all DA experiments, the suffix _PAR indicates that, in addition to state updates, the saturated hydraulic conductivity (log K_s) was updated every seven days using a damping factor of 0.1. The _PAR runs were initialized from the same spun-up equilibrium state as their corresponding state-update experiments, and the gradual parameter updates ensured that changes remained small and did not disturb the equilibrium state too much, thereby avoiding the need for additional spin-ups. Furthermore, parameter validation involved applying K_s updated from one year to OL simulations in other years (e.g., using updated K_s from 2016 in 2017-2018)."

2. Table 3 would benefit from some narrative text to describe the different experiments, in words, to help better describe them.

Response: Your point is taken. Following the advice, we have added more descriptions of the data assimilation experiments listed in Table 3 to facilitate understanding. The new text has been added in Section 3.2 Configuration of Data Assimilation Experiments (lines 351-368 in the revised manuscript) and reads:

"11 DA experiments (Table 3) were conducted to assess assimilation performance, differing in observation type, state vector composition, and localization strategy. The open loop (OL) experiment, performed without assimilation, served as the reference for DA comparisons. SM_DA assimilated daily SM observations from CRNS (observation error of 0.03 cm^3/cm^3) with 100 km localization radius. GWL_DA assimilated weekly GWL observations, with an observational error of 0.05 m, using a 5 km localization radius, updating only hydraulic head (h) in the saturated zone. FC_DA assimilated both SM and GWL using the fully coupled DA strategy, with the state vector including h and θ in all subsurface layers. θ and h were updated daily and weekly, respectively, both with a 5 km localization radius. WC_DA used the weakly coupled scheme, with h updated only in the saturated zone and θ only in the unsaturated zone; all other settings were the same as FC_DA. Moreover, WC_DA_r followed the same setup as WC_DA, except that the localization radius differed between the two variables: 5 km for GWL and 100 km for SM. For all DA experiments, the suffix _PAR indicates that, in addition to state updates, the saturated hydraulic conductivity (log K_s) was updated every seven days using a damping factor of 0.1. The _PAR runs were initialized from the same spun-up equilibrium state as their corresponding state-update experiments, and the gradual parameter updates ensured that changes remained small and did not disturb the equilibrium state too much, thereby avoiding the need for additional spin-ups. Furthermore, parameter validation involved applying K_s updated from one year to OL simulations in other years (e.g., using updated K_s from 2016 in 2017-2018)."

3. In the experiments that assimilate model derived outputs (such as WTD) and those that also adjust ln(Ksat) there does not appear to be a difference in temporal behavior. That is, often if there is bias in say soil moisture it will drift back to a value different than the observation after the assimilation period over time. Adjusting ln(Ksat) should help correct this model "bias" but I'm not seeing this behavior in the results (but agree with the overall improvement the authors point out). I'm wondering if they can comment on this more?

Response: We thank the reviewer for this valuable observation. In our experiments, several factors may limit the visible differences in temporal evolution between simulations with and without saturated hydraulic conductivity (K_s) updates. First, model biases are influenced not only by K_s but also by other factors, such as forcing uncertainty and structural model errors, which can dominate the temporal evolution of soil moisture and groundwater states. Second, K_s updates were applied with a fixed damping factor of 0.1, which constrained the adjustment range, particularly for slowly responding groundwater states. Nevertheless, adjusting K_s during assimilation can still reduce model bias in variables. As a result, *while temporal patterns may appear similar, experiments with parameter updates show clear improvements in performance metrics and long-term mean states. Independent validations using the revised K_s confirmed enhanced predictions of both GWL and SM. We have added a brief discussion of these points in Section 5.2 (lines 819-833) to clarify:*

"The primary objective of multivariate DA is to enhance the accuracy of both state variables and associated parameter estimates. This research focused on updating K_s, identified as a critical parameter for the subsurface groundwater system. Although the temporal evolution of assimilated states may not show large differences between experiments with and without K_s updates, this does not imply that parameter updating is ineffective. For example, in our experiments, K_s updates led to reductions in ubRMSE of more than 10% for both GWL and SM compared with state-only assimilation. However, the immediate temporal impact of K_s updates may be limited, partly due to the constrained adjustment range applied by the fixed damping factor (0.1) and the slow response of groundwater states. Moreover, model biases are also influenced by other factors, including forcing uncertainty and structural model errors, which may play a dominant role in the temporal evolution of SM and groundwater states. Nevertheless, parameter-updating experiments improved performance metrics and long-term mean states, demonstrating their value in correcting systematic model biases that cannot be fully addressed by state assimilation alone. Independent validations using the revised K_s confirmed enhanced predictions of both GWL and SM. These results highlight the importance of considering both state and parameter updates in multivariate assimilation frameworks to achieve more reliable hydrologic predictions."