“Enhancing hydrological representation of the Brahmaputra basin through terrestrial water storage and surface soil moisture Data Assimilation” [egusphere-2025-5625]

General comment:

This manuscript presents a methodologically innovative contribution to large-scale hydrological data assimilation by integrating GRACE/GRACE-FO Terrestrial Water Storage (TWS) anomalies into the W3RA land surface model using an Ensemble Kalman Filter (EnKF) framework with a novel **model space mixed localization** scheme. The study is applied to the Brahmaputra basin, a hydrologically complex and data-scarce region, and demonstrates improvements in both TWS and streamflow simulations at daily temporal resolution. The multi-variable validation approach, encompassing TWS, streamflow, and surface soil moisture (SSM), strengthens the credibility of the results.

The paper addresses a relevant scientific problem and makes genuine contributions to the field. However, several major concerns must be addressed before the manuscript can be considered for publication in the Hydrology and Earth System Sciences journal. I believe it needs “major revisions”. Some suggestions for revisions are as follows.

Major comments:

1. The authors employ an ensemble of N=30 members in the EnKF framework. Given that the W3RA model state vector encompasses a large number of variables across the Brahmaputra basin, this ensemble size appears insufficient to adequately sample the model's uncertainty space and may lead to significant sampling errors and filter degeneracy. The authors provide no explicit justification for this choice, nor do they present a sensitivity analysis demonstrating that N=30 yields stable and converged results. It is strongly recommended that the authors either:

- Provide a formal justification based on the effective degrees of freedom of the system, or;
- Include a sensitivity analysis showing key metrics (e.g., NSE, RMSE, ensemble spread) as a function of ensemble size (e.g., N = 20, 30, 50, 100).

2. The Brahmaputra basin contains significant glaciated areas, and GRACE/GRACE-FO TWS signals include a long-term trend associated with glacial mass loss. The authors appear to assimilate the full TWS signal and subsequently subtract the glacial component *a posteriori*. This approach raises important questions:

- Does the assimilation of the glacial trend introduce systematic biases into the model state variables (soil moisture, groundwater) that are not physically meaningful?
- How does this *a posteriori* correction compare to an approach where the glacial signal is removed *prior* to assimilation?

The authors should provide a more explicit discussion of the implications of this methodological choice and, if possible, a quantitative comparison between both approaches.

3. While the assimilation improves TWS estimates, the manuscript reports a non-trivial reduction in Nash-Sutcliffe Efficiency (NSE) for streamflow at certain gauging stations. This result is concerning and warrants a more thorough investigation. Specifically:

- What are the dominant mechanisms driving this degradation? Possible causes include cross-variable error covariances, inadequate localization, or structural limitations of the W3RA baseflow parameterization.
- Is the W3RA model's baseflow representation adequate for the Brahmaputra's complex glacial and snowmelt-driven hydrological regime?
- Have the authors considered recalibrating the model after assimilation to mitigate this effect?

A dedicated subsection analyzing the sources of streamflow degradation would substantially strengthen the manuscript.

4. The validation of surface soil moisture relies on WaterGAP model outputs as a reference dataset rather than on independent observational data. This introduces a circular dependency, as WaterGAP is itself a model subject to its own structural and parametric uncertainties. The authors should:

- Quantify the uncertainty associated with WaterGAP SSM estimates and discuss how this uncertainty propagates into the validation conclusions.
- Consider supplementing the validation with observational datasets such as ESA CCI Soil Moisture, SMAP, or in-situ measurements where available.

5. The proposed model space mixed localization scheme is a central methodological contribution of this work. However, the manuscript does not present a systematic sensitivity analysis of the localization radii applied to the different model state variables. Given that localization is known to critically influence EnKF performance, the authors should demonstrate:

- How sensitive are the results to the chosen localization radii?
- What criteria were used to select the final parameter values?
- Were alternative localization configurations tested?

6. The manuscript reports quantitative estimates of land water loss in the Brahmaputra basin. However, no uncertainty bounds (e.g., confidence intervals derived from the ensemble spread, or sensitivity to model assumptions) are provided for these estimates. Given the policy relevance of these figures, particularly in the context of climate change and transboundary water management, the authors must include a rigorous uncertainty analysis accompanying all reported water loss values.

Minor comments:

1. **Table 1:** The notation used to describe model state variables is inconsistent with the notation employed in the equations. A unified nomenclature should be adopted throughout the manuscript.
2. **Equation 6:** There appears to be a typographical error in the formulation of the observation operator. The authors should verify the consistency of this equation with the surrounding text and correct it accordingly.
3. **Definition of SSM:** The manuscript uses the term "surface soil moisture" inconsistently, at times referring to the top soil layer and at others to a vertically integrated quantity. A precise and consistent definition should be provided at first use.
4. **Asynchronous Assimilation:** The authors propose a hypothesis regarding the effects of asynchronous assimilation on streamflow performance. This hypothesis, while plausible, remains speculative and is not supported by direct evidence within the manuscript. It should either be tested explicitly or clearly framed as a working hypothesis requiring future investigation.
5. **Relegation of Results to Appendices:** Several results that appear central to the evaluation of the proposed localization scheme are presented in appendices. The authors should consider whether these results merit inclusion in the main body of the manuscript to improve readability and scientific transparency.
6. **Model Recalibration:** Given the known structural limitations of W3RA in glacially influenced basins, the authors should discuss whether a recalibration of the model prior to assimilation was considered and, if not, justify this decision.
7. **GRACE Spatial Resolution:** The coarse spatial resolution of GRACE/GRACE-FO (~300 km) relative to the spatial heterogeneity of the Brahmaputra basin may limit the physical interpretability of the assimilated signal at sub-basin scales. The authors should explicitly discuss this limitation and its potential impact on the results.

Data Availability:

The Zenodo DOI provided for data availability appears to be reserved but not yet publicly accessible. The authors should confirm that all data and code necessary to reproduce the results will be made available upon publication, in accordance with the journal's open science policy.

Conclusion:

This manuscript makes a genuine and timely contribution to the field of hydrological data assimilation in data-scarce, high-mountain basins. The proposed localization scheme is innovative, the validation framework is multi-variable, and the application to the Brahmaputra basin is scientifically relevant. Nevertheless, the major concerns outlined above, particularly regarding ensemble size justification, glacial signal treatment, streamflow degradation, and uncertainty quantification, must be thoroughly addressed before the manuscript can be recommended for publication.