Analyzing the performance of ensemble-based disaggregation in GRACE(-FO) Terrestrial Water Storage Data Assimilation and exploring a deterministic alternative

Leire Retegui-Schiettekatte[(1)], Maike Schumacher[(1)], Fan Yang[(1)], Henrik Madsen[(2)], and Ehsan Forootan[(1)]

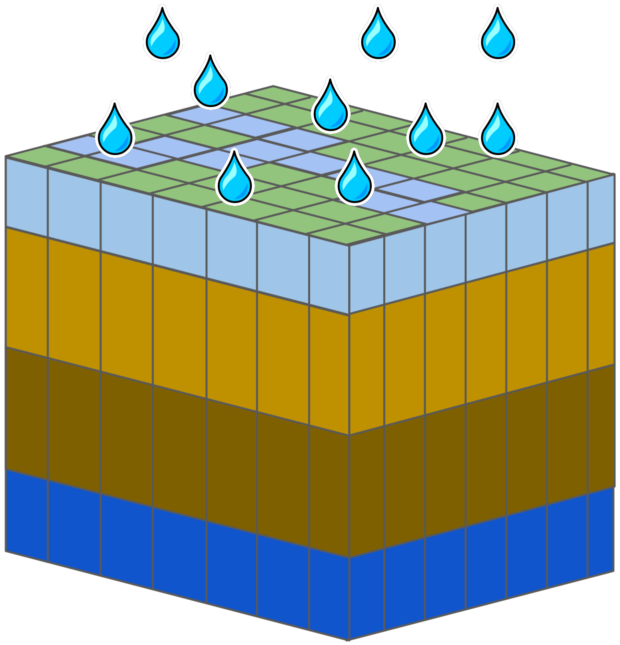
(1) Department of Sustainability and Planning, Aalborg University (Denmark)
(2) DHI (Denmark)

DANSk-LSM
INDEPENDENT RESEARCH FUND DENMARK

AALBORG UNIVERSITY

Index

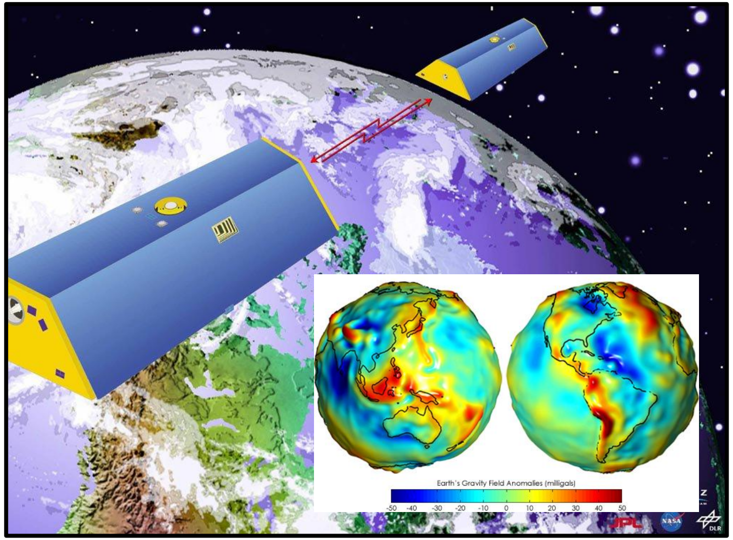
Hydrological models



- Input: meteorological forcing
- Output: water storage and hydrological fluxes

- Benefits: integral high-resolution representation
- Limitations: errors, unrepresented processes…

Total Water Storage



GRACE

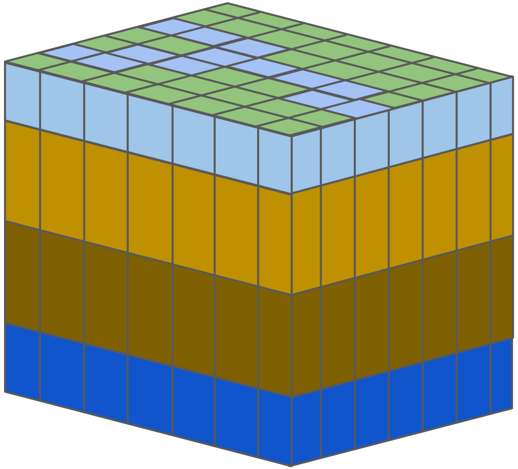
2002 2017

GRACE-FO

2019 present

Gravity Recovery and Climate Experiment

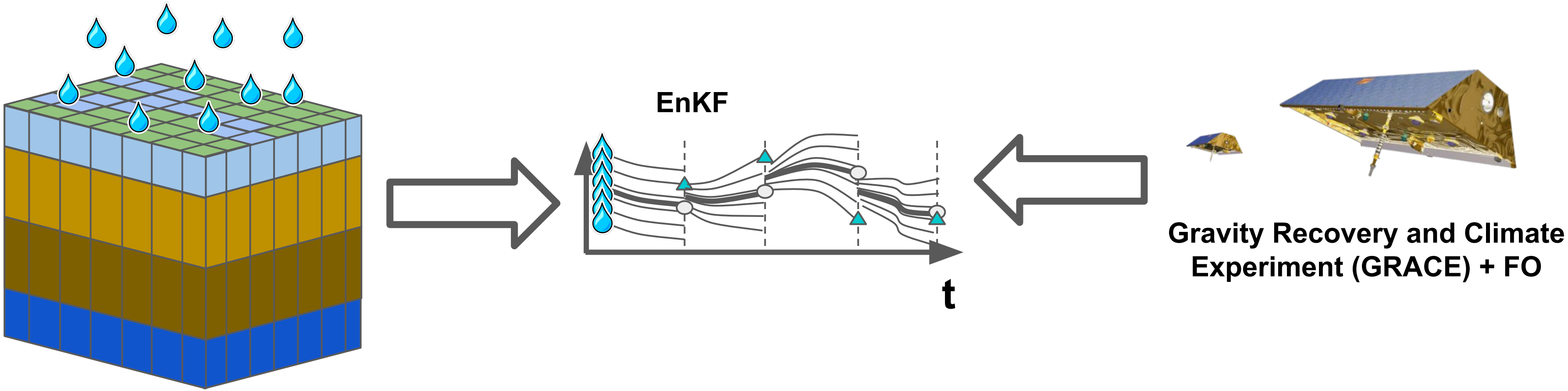
TWS



Monthly

~ 200 - 300 km

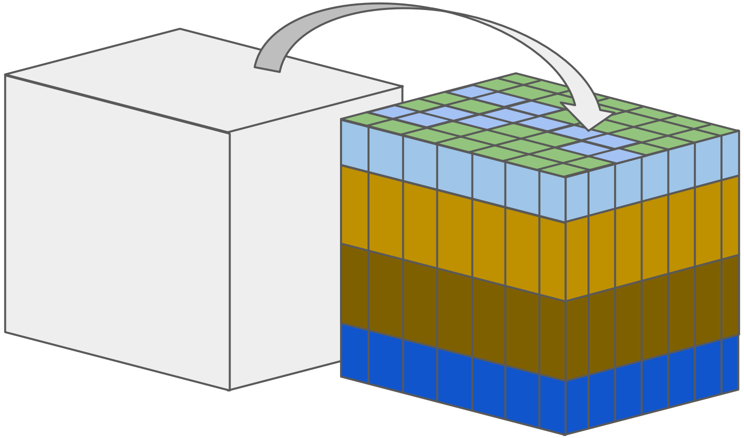
DA combines benefits



- Integral representation
- High resolution
- Increased realism

Zaitchik et al. (2008),
van Dijk et al. (2014),
Girotto et al. (2016),
Schumacher et al. (2018)…

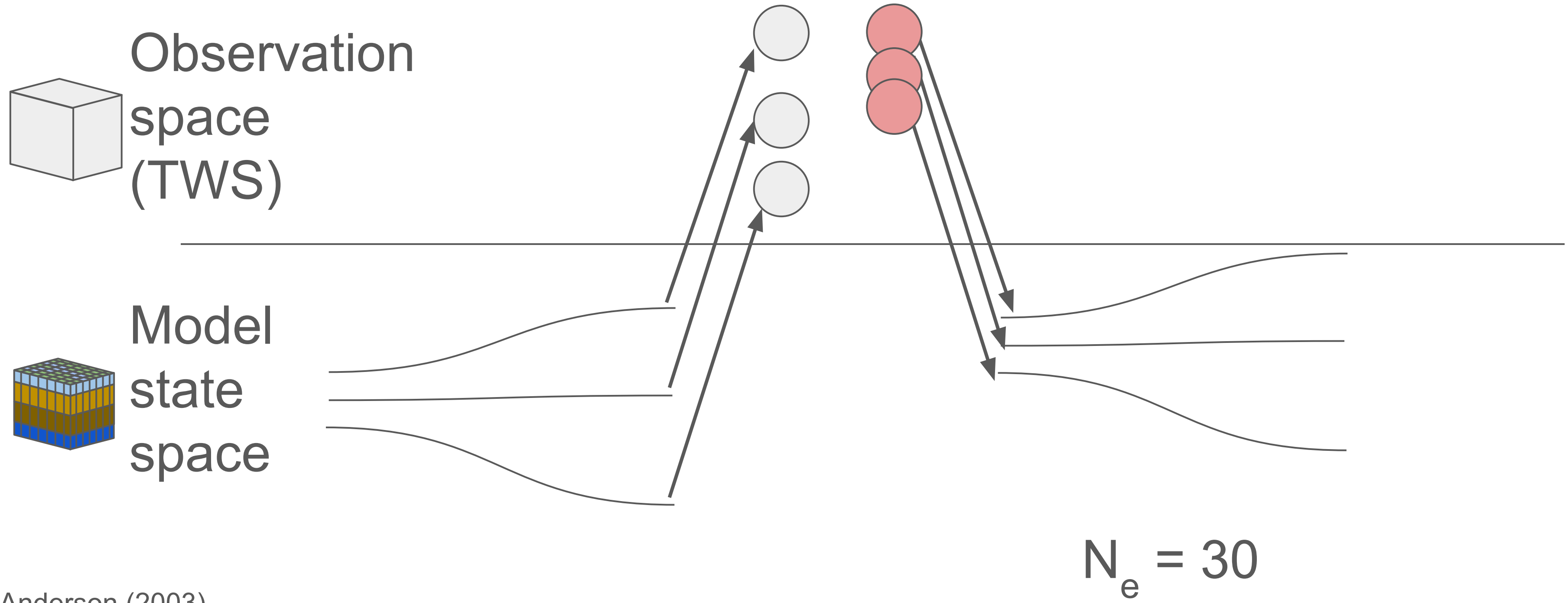
Limitations in ensemble-based TWS disaggregation



- Inaccurate vertical disaggregation degrades some individual state variables

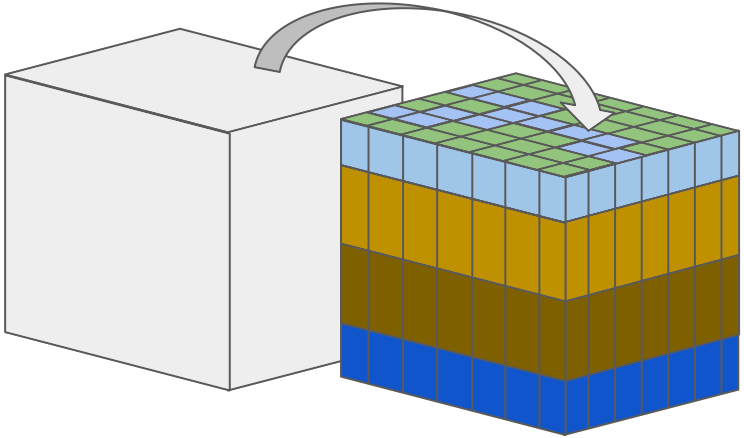
Girotto et al. (2016),
Girotto et al. (2019),
Tangdamrongsub et al. (2020),
Schulze et al. (2024) …

Limitations in ensemble-based TWS disaggregation



Anderson (2003)

Limitations in ensemble-based TWS disaggregation



Previous solutions:

- Multi sensor DA → conflicts
- Localization

Girotto et al. (2019),
Retegui-Schiettekatte et al. (2025)...

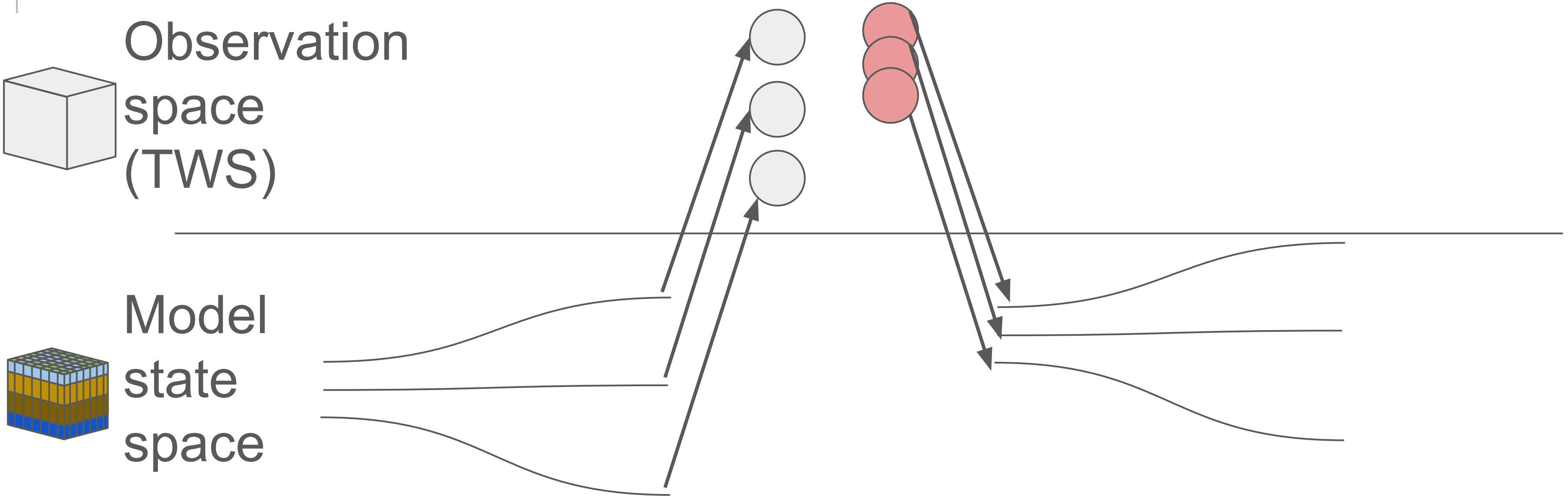
2 objectives:

Analyze model update-response to understand impact on individual storages

Propose and test novel rescaling disaggregation approach (EnKF-R)

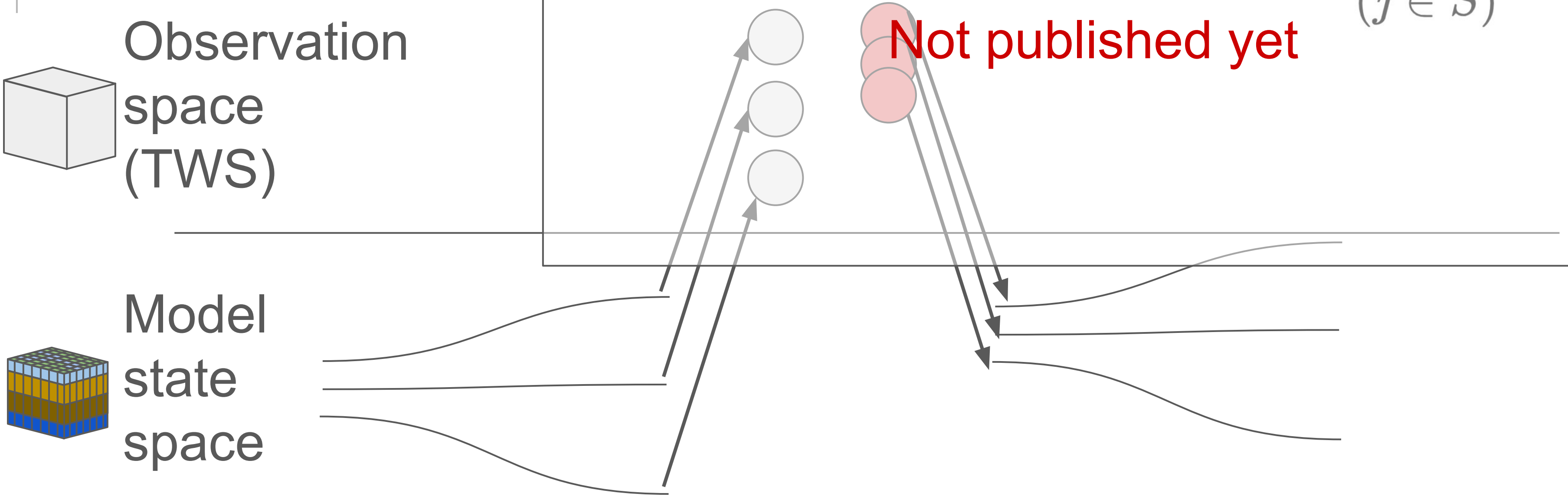
Novel approach

$$\cancel{\mathbf{X}_k^+ = \mathbf{X}_k^- + \mathbf{C}_{(\mathbf{x}_k^-, \mathbf{y}_k^-)} \mathbf{C}_{\mathbf{y}_k^-}^{-1} (\mathbf{Y}_k^+ - \mathbf{Y}_k^-)}$$



Novel approach

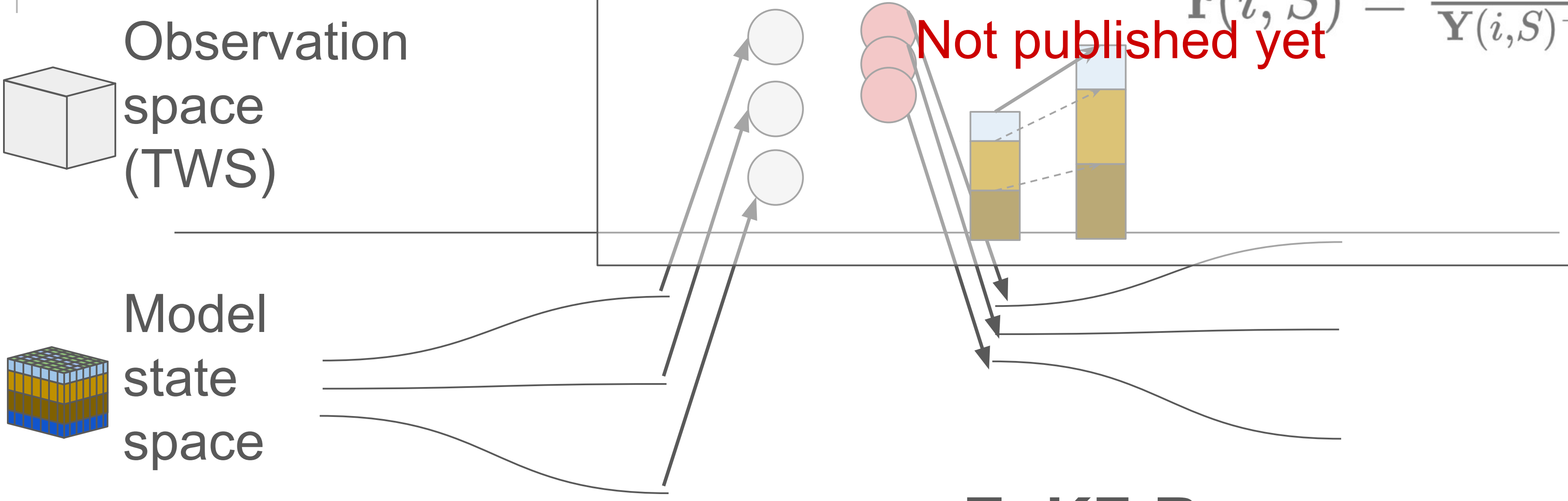
$$\mathbf{X}_k^+(i,j) = \mathbf{X}_k^-(i,j) + \frac{\mathbf{X}_k^-(i,j)}{\mathbf{Y}_k^-(i,S)}\left(\mathbf{Y}_k^+(i,S) - \mathbf{Y}_k^-(i,S)\right) \qquad (j \in S)$$



Novel approach

$$\mathbf{X}^{+}(i, j \in S) = \mathbf{r}(i, S) \cdot \mathbf{X}^{-}(i, j \in S)$$

$$\mathbf{r}(i, S) = \frac{\mathbf{Y}(i,S)^{+}}{\mathbf{Y}(i,S)^{-}}$$



EnKF-R

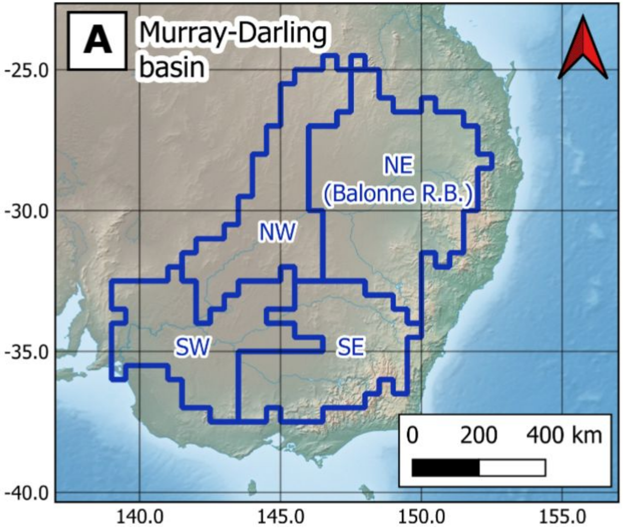
2 objectives:

Analyze model update-response to understand impact on individual storages

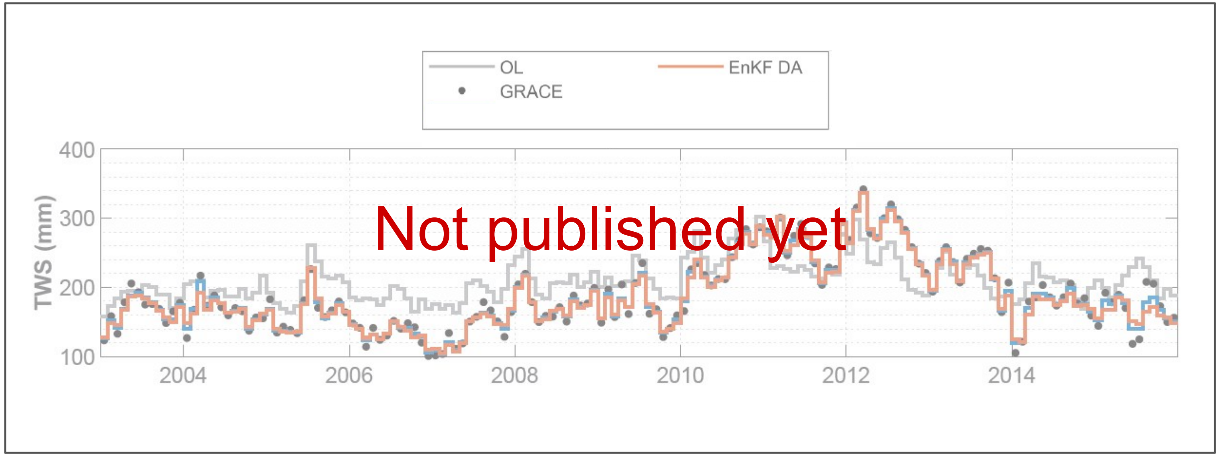
Propose and test novel rescaling disaggregation approach (EnKF-R)

Experimental setting

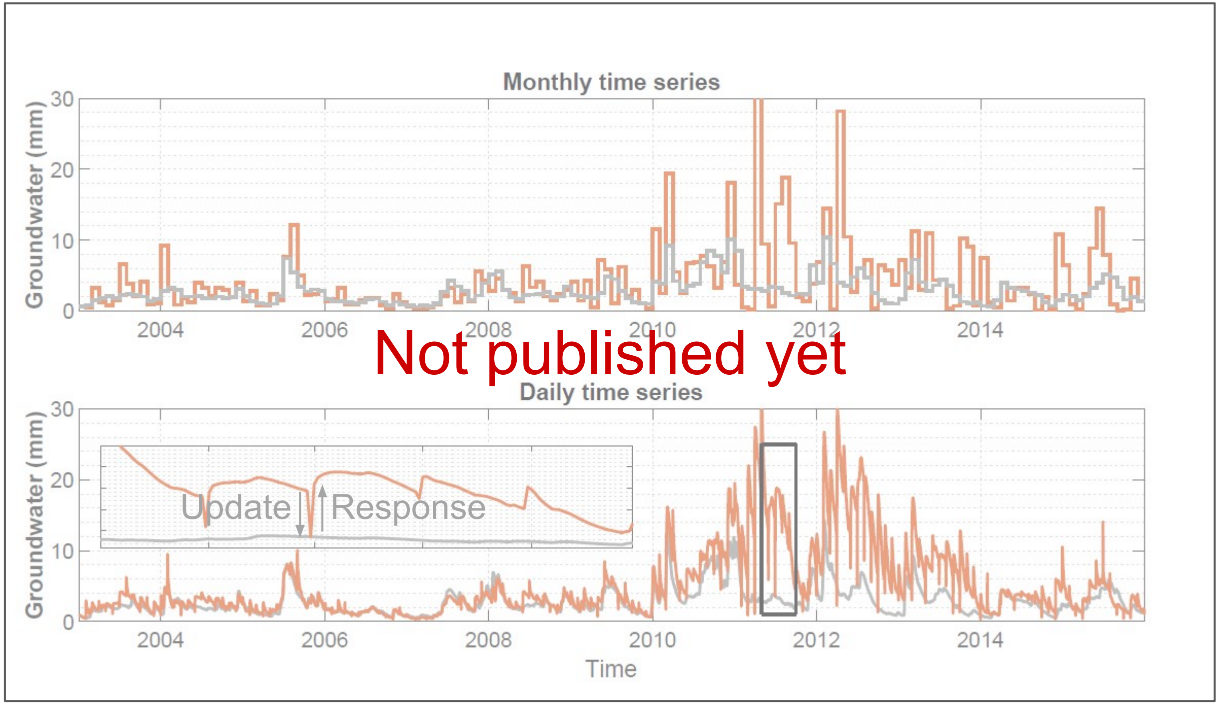
- Model: W3RA, daily 10km resolution
- Ensemble perturbation
  - Precipitation
  - Nine model parameters
- Forcing data: ERA5 + ERA5-Land
- GRACE TWS product: ITSG-18 (sub-basin averaged)



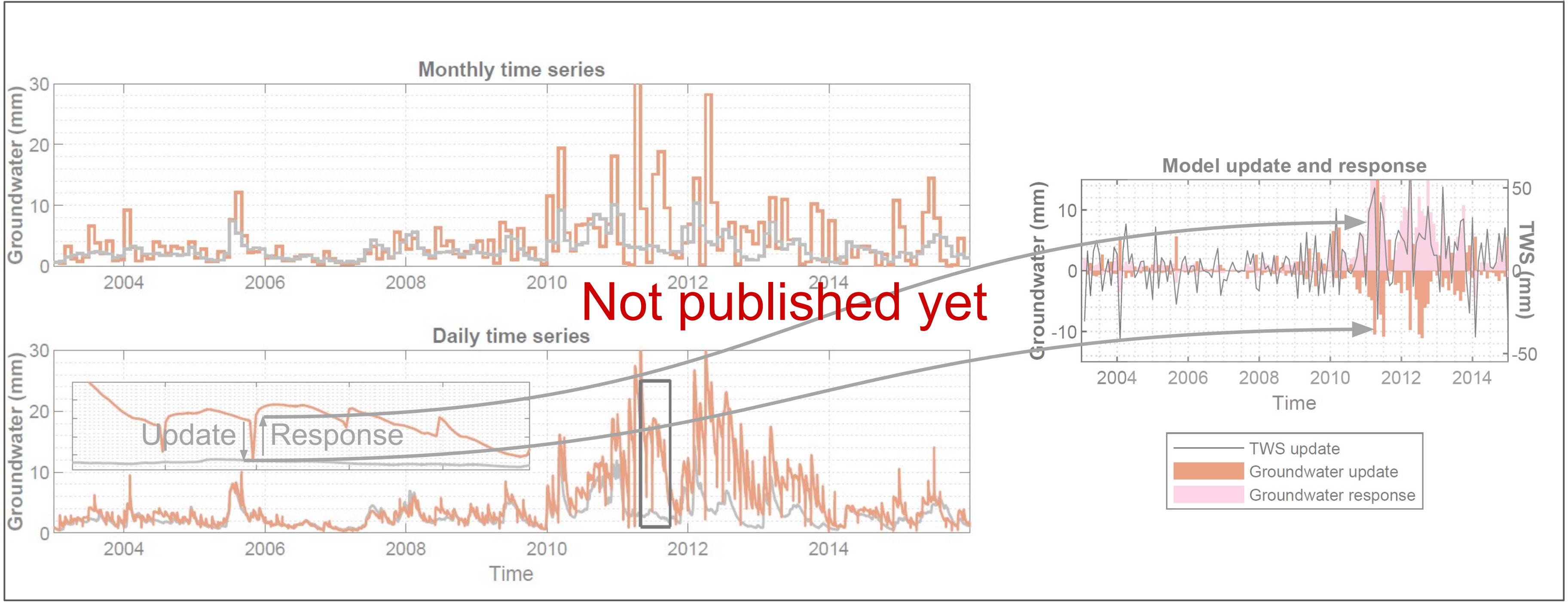
TWS dynamics (EnKF)



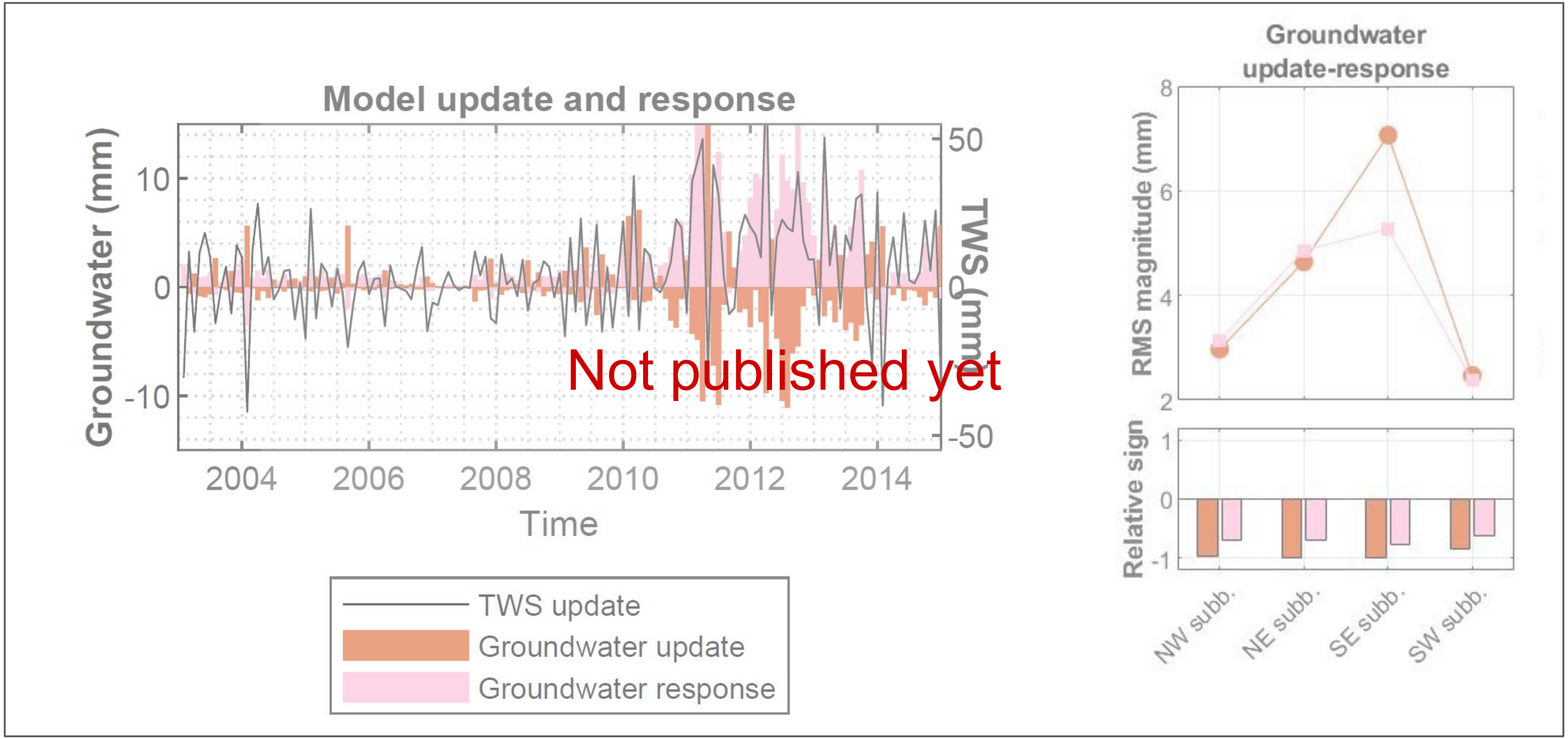
Groundwater dynamics (EnKF).



Measuring of model update-response (EnKF).



Measuring of model update-response

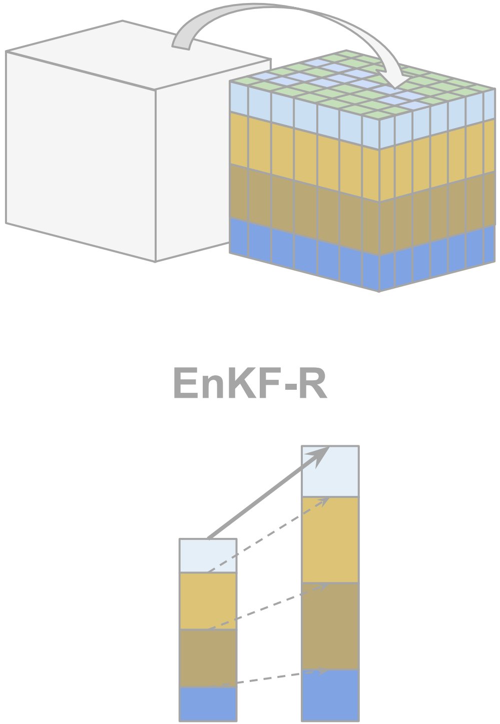


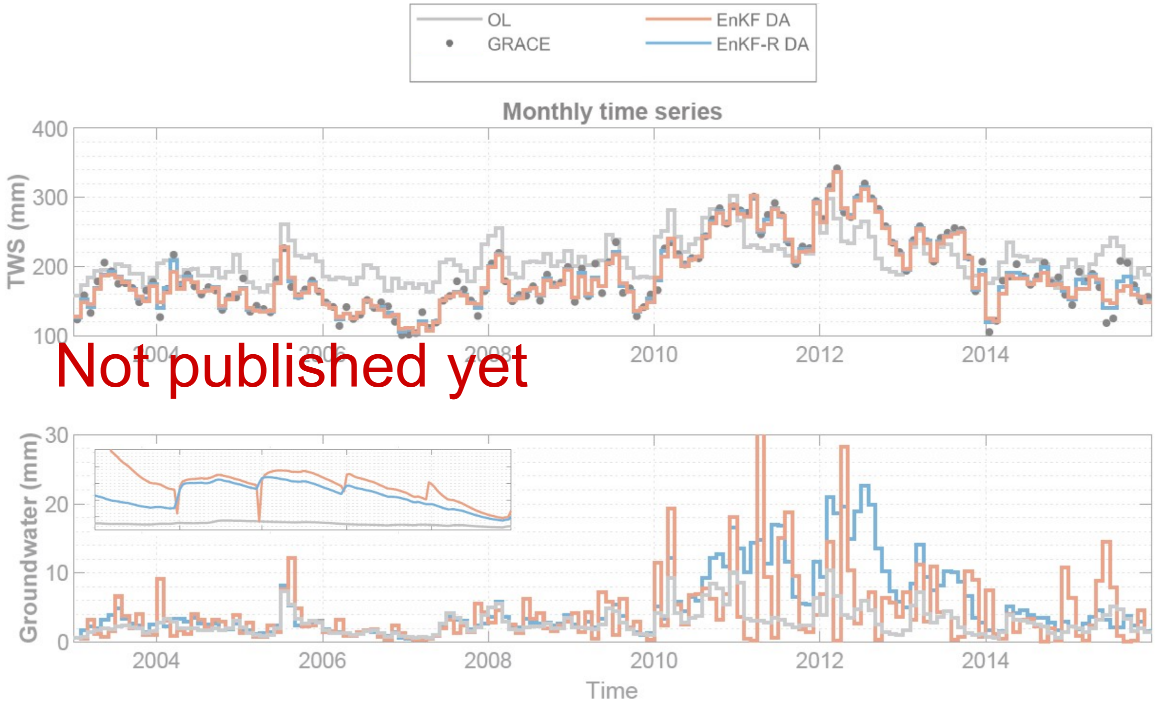
2 objectives:

Analyze model update-response to understand impact on individual storages

Propose and test novel rescaling disaggregation approach (EnKF-R)

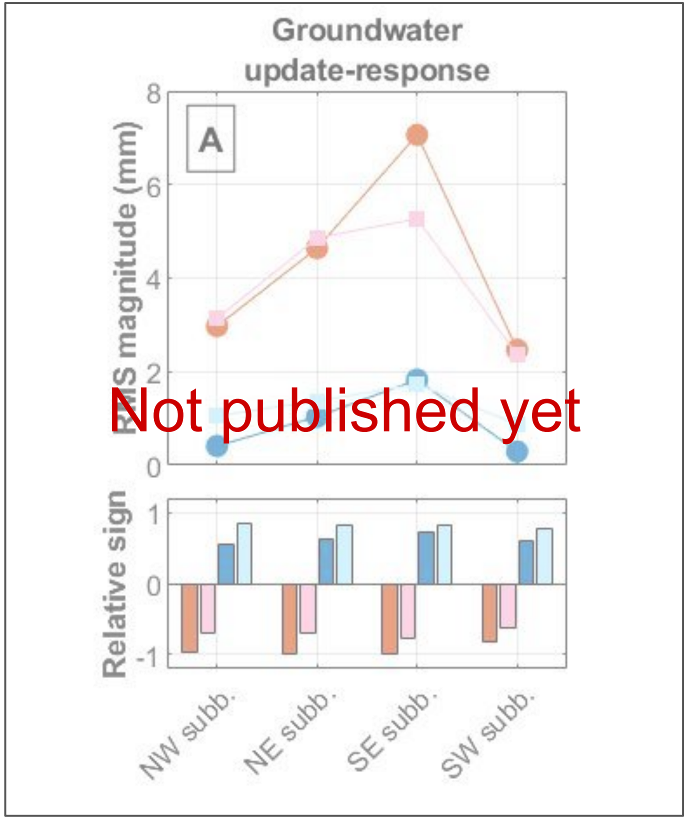
TWS and groundwater dynamics



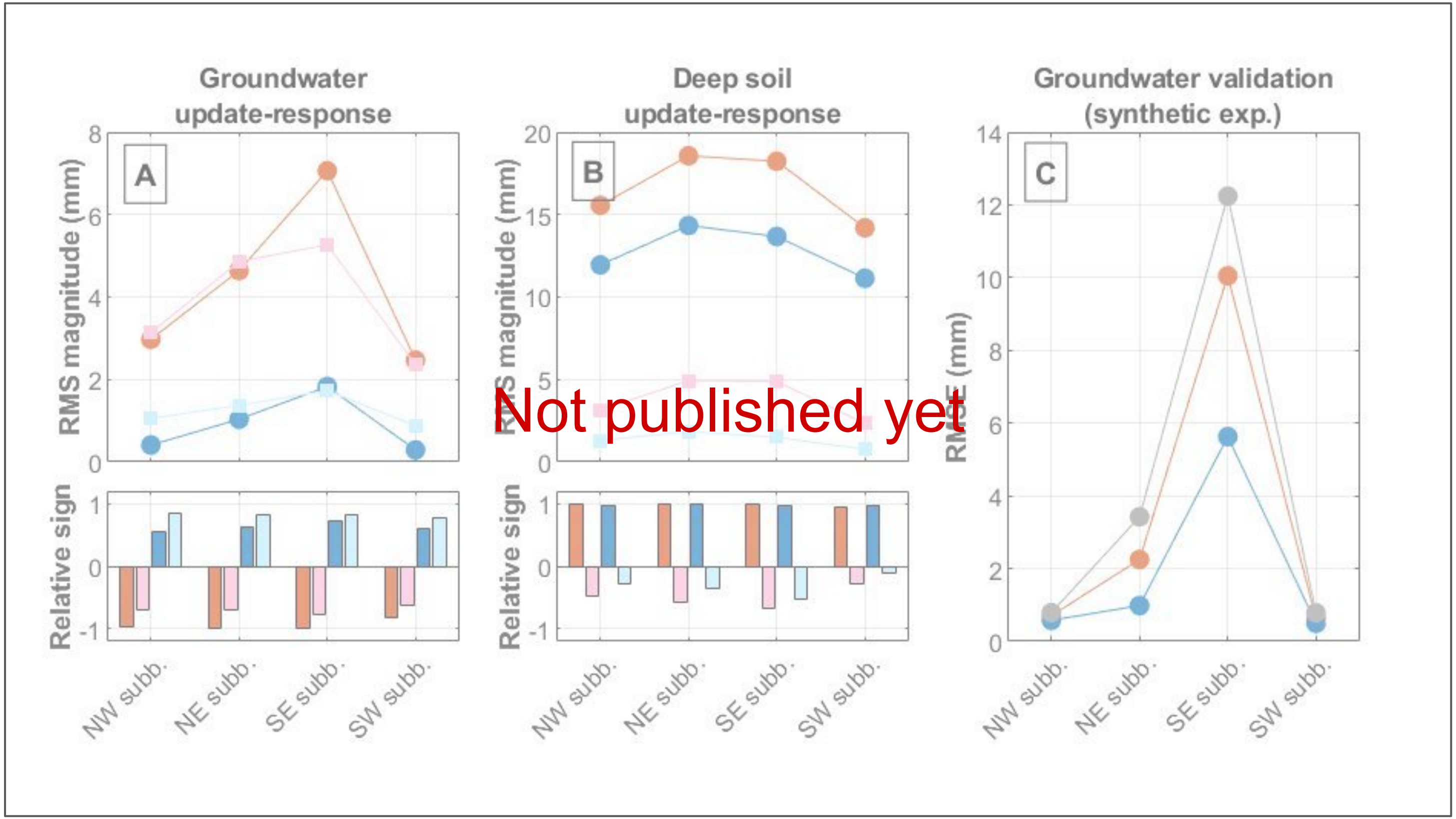


Not published yet

Groundwater update-response

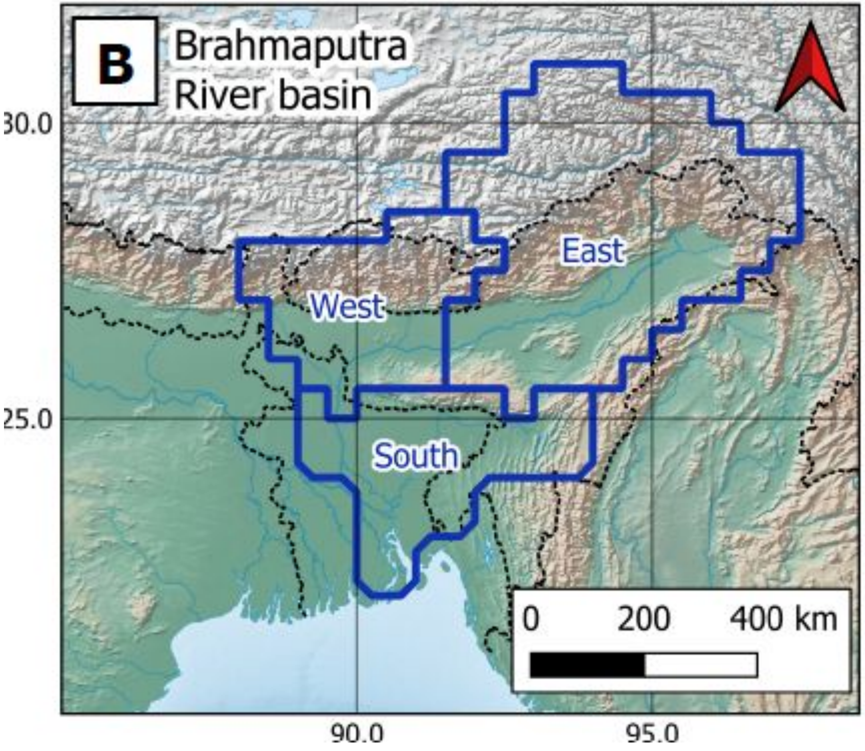


General evaluation & validation (Murray-Darling)

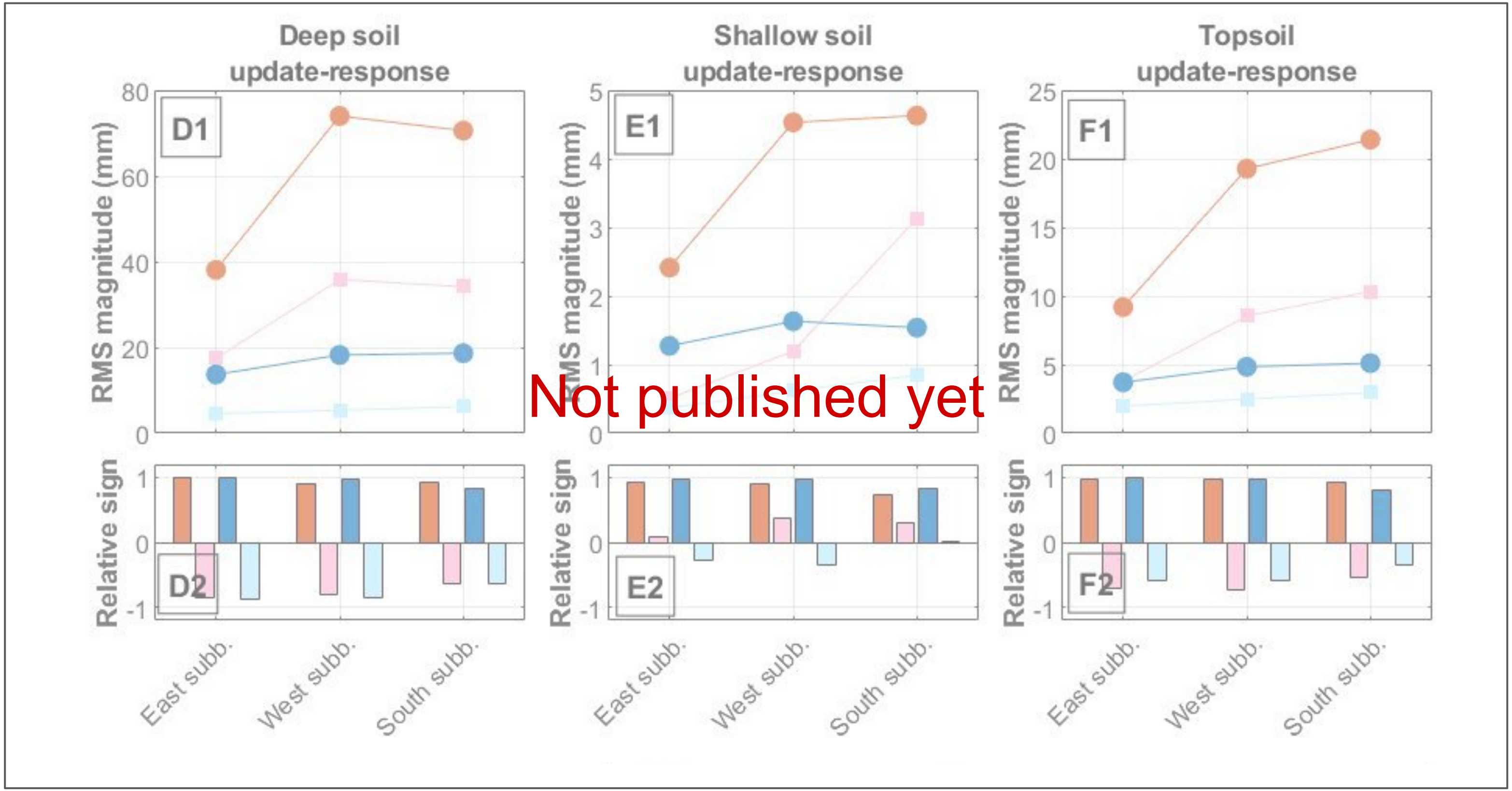


Not published yet

General evaluation & validation (Brahmaputra)

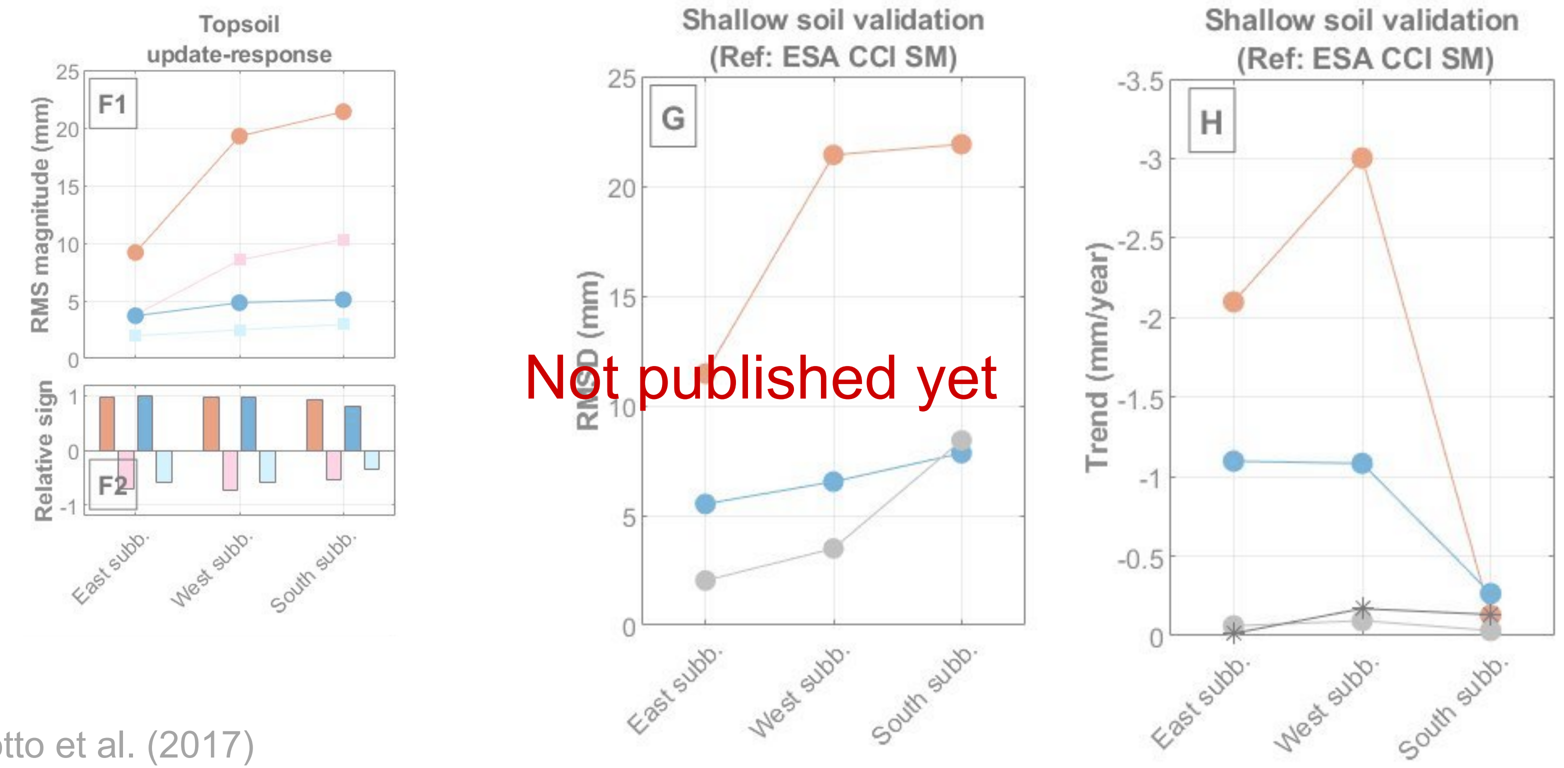


General evaluation & validation (Brahmaputra)



Not published yet

General evaluation & validation (Brahmaputra)



Girotto et al. (2017)

Conclusions

Update-response dynamics reveal additional insights on impact of TWS DA on individual storage components

Not published yet

EnKF-R can achieve similar results as ensemble-based disaggregation while avoiding drawbacks of the latter

Conclusions

Update-response dynamics reveal additional insights on impact of TWS DA on individual storage components

EnKF-R can achieve similar results as ensemble-based disaggregation while avoiding drawbacks of the latter

Not published yet

Addtional strengths: EnKF-R is computationally less expensive

Limitations:

- Discontinuities between sub-basins
- Ensemble spread of individual estimates
- Transferability to other basins?

References

B. F. Zaitchik, M. Rodell, and R. H. Reichle, “Assimilation of GRACE Terrestrial Water Storage Data into a Land Surface Model: Results for the Mississippi River Basin,” *Journal of Hydrometeorology*, vol. 9, no. 3, pp. 535–548, Jun. 2008, doi: 10.1175/2007JHM951.1.

A. I. J. M. van Dijk, L. J. Renzullo, Y. Wada, and P. Tregoning, “A global water cycle reanalysis merging satellite gravimetry and altimetry observations with a hydrological multi-model ensemble,” *Hydrology and Earth System Sciences*, vol. 18, no. 8, pp. 2955–2973, Aug. 2014, doi: 10.5194/hess-18-2955-2014.

M. Girotto, G. J. M. De Lannoy, R. H. Reichle, and M. Rodell, “Assimilation of gridded terrestrial water storage observations from GRACE into a land surface model,” *Water Resources Research*, vol. 52, no. 5, pp. 4164–4183, 2016, doi: 10.1002/2015WR018417.

M. Schumacher *et al.*, “Improving drought simulations within the Murray-Darling Basin by combined calibration/assimilation of GRACE data into the WaterGAP Global Hydrology Model,” *Remote Sensing of Environment*, vol. 204, pp. 212–228, Jan. 2018, doi: 10.1016/j.rse.2017.10.029.

M. Girotto, R. H. Reichle, M. Rodell, Q. Liu, S. Mahanama, and G. J. M. De Lannoy, “Multi-sensor assimilation of SMOS brightness temperature and GRACE terrestrial water storage observations for soil moisture and shallow groundwater estimation,” *Remote Sensing of Environment*, vol. 227, pp. 12–27, Jun. 2019, doi: 10.1016/j.rse.2019.04.001.

N. Tangdamrongsub *et al.*, “Multivariate data assimilation of GRACE, SMOS, SMAP measurements for improved regional soil moisture and groundwater storage estimates,” *Advances in Water Resources*, vol. 135, p. 103477, Jan. 2020, doi: 10.1016/j.advwatres.2019.103477.

K. Schulze, J. Kusche, H. Gerdener, P. Döll, and H. Müller Schmied, “Benefits and Pitfalls of GRACE and Streamflow Assimilation for Improving the Streamflow Simulations of the WaterGAP Global Hydrology Model,” *Journal of Advances in Modeling Earth Systems*, vol. 16, no. 10, p. e2023MS004092, 2024, doi: 10.1029/2023MS004092.

J. L. Anderson, “A Local Least Squares Framework for Ensemble Filtering,” *Monthly Weather Review*, vol. 131, no. 4, pp. 634–642, Apr. 2003, doi: 10.1175/1520-0493(2003)131<0634:ALLSFF>2.0.CO;2.

L. Retegui-Schiettekatte, M. Schumacher, H. Madsen, and E. Forootan, “Assessing daily GRACE Data Assimilation during flood events of the Brahmaputra River Basin,” *Science of The Total Environment*, vol. 975, p. 179181, May 2025, doi: 10.1016/j.scitotenv.2025.179181.

M. Girotto *et al.*, “Benefits and pitfalls of GRACE data assimilation: A case study of terrestrial water storage depletion in India,” *Geophysical Research Letters*, vol. 44, no. 9, pp. 4107–4115, 2017, doi: 10.1002/2017GL072994.

Thank you!

Leire Retegui-Schiettekatte

leirears@plan.aau.dk

AALBORG UNIVERSITY