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Exploring GRACE and GRACE-FO data to estimate the groundwater component of a Digital Twin of the terrestrial water cycle

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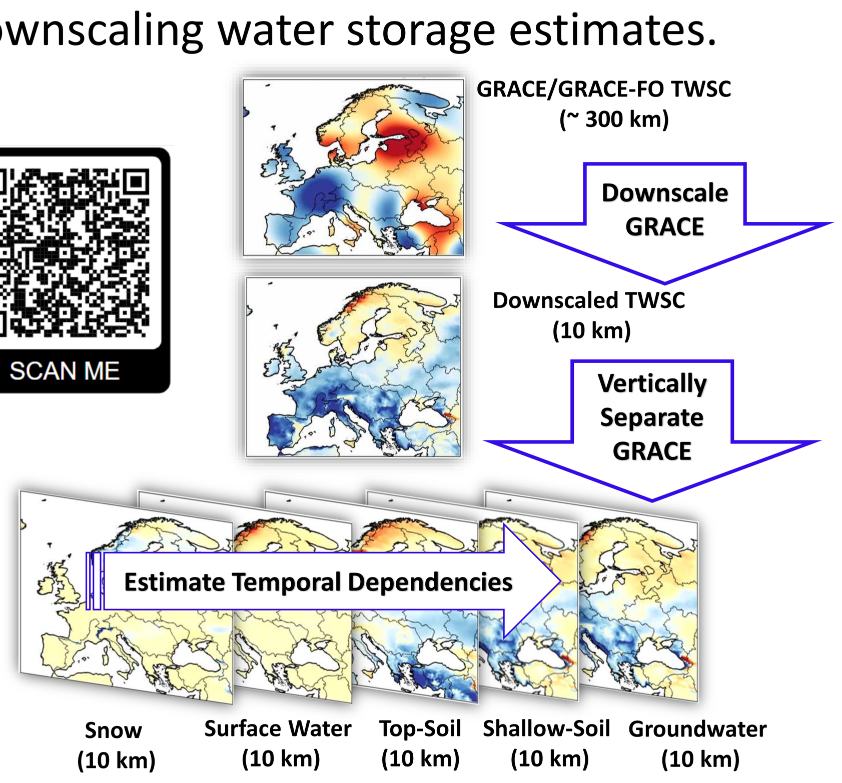
Introduction

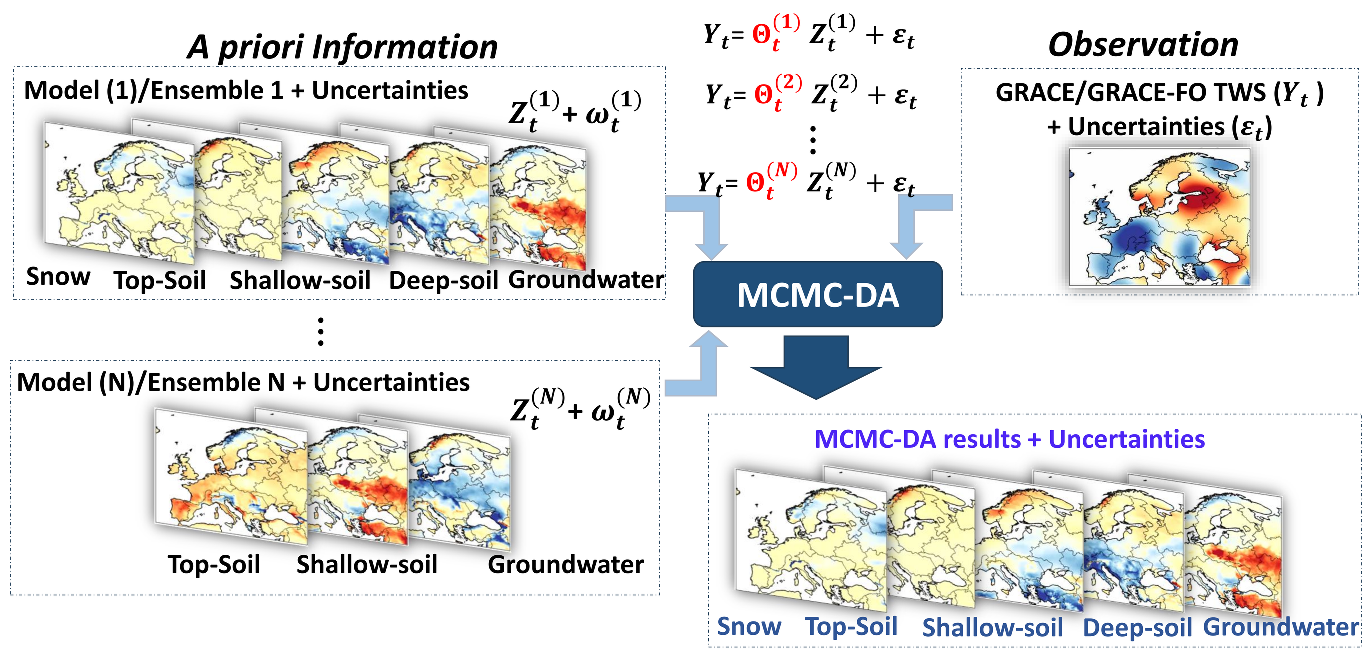
As the climate warms, hydrological processes become more complex, making the development of accurate digital twins of the terrestrial water cycle increasingly crucial for predicting water-related hazards and managing water resources effectively. In this study, we **investigate the use of satellite observations** of the Earth's time-variable gravity fields from the Gravity Recovery and Climate Experiment (GRACE) and its Follow-On mission (GRACE-FO), to **estimate Terrestrial Water Storage (TWS)** and to **constrain water storage** representation of large-scale hydrological models within **Europe**. The implementation follows a multivariate state-space Bayesian model-data fusion to merge a priori **0.1° resolution** water storage estimates with the TWS observed by **GRACE/GRACE-FO** and **surface soil moisture** from **ESA-CCI**. The estimated groundwater storage are compared against groundwater estimates of other models and data processing strategies. Future investigations will be performed against in-situ groundwater network within Europe and the GNSS measurements. In the context of the *Digital Twin Earth Hydrology Next Project* funded by ESA, we will also investigate the feasibility of the (Interferometric) Synthetic Aperture Radar (InSAR) and SAR techniques for downscaling water storage estimates.

SCAN ME



Method

Bayesian-Based Markov Chain Monte Carlo Data Assimilation (MCMC-DA) is developed by Mehrnegar et al. (2021). This technique provides a general formulation to fuse satellite data into models. This can be implemented as **single model, multi-model, single observation, and multi-sensor fusions**. For example, a simultaneous fusion of SMAP and GRACE(-FO) data with the 0.1° resolution W3RA model is demonstrated in Mehrnegar et al. (2023), and a constraining process to separate surface deformation signals from water storage estimates is shown in Forootan and Mehrnegar (2022) using GNSS and GRACE(-FO) data.



Within MCMC-DA, the joint posterior distribution of the unknown state parameters ($\theta_t^{(n)}$) and temporal dependencies between them are estimated through a combination of:

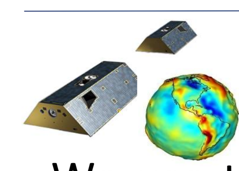
- Gibbs sampling
- Metropolis-Hasting algorithm
- Forward-filtering, backward-smoothing recursion
- Bayesian Model Averaging

SCAN ME

Setup of MCMC-DA:

- The ensemble size is 30 - 75 - 90 member.
- The assimilation window size is daily.
- Experiment Date: 2003 onward.
- Assimilated observations: GRACE/GRACE-FO and Soil Moisture (can be added).
- Validated observations: In-Situ groundwater

Data



GRACE/GRACE-FO TWS

We use the **Release-6 (RL06)** Level-2 (L2) monthly gravity solutions provided by the **Center for Space Research (CSR)**, covering **January 2003 – June 2017** (GRACE) and **June 2018 – December 2024** (GRACE-FO).

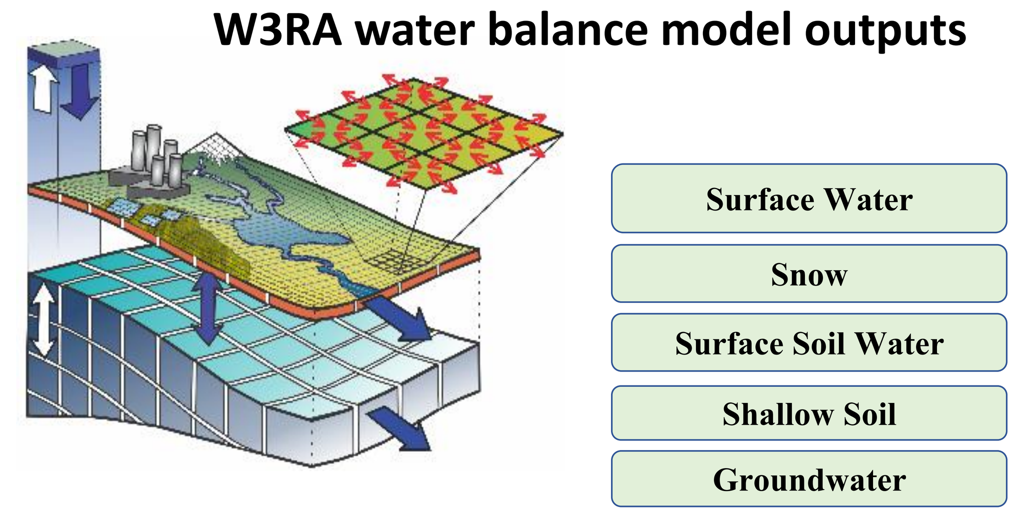
Preprocessing steps:

- Replace **degree-1** and **C20** and **C30**.
- Remove **Glacial Isostatic Adjustment (GIA)** effects using the **ICE-6G-D (VM5a)** model.
- Apply an **anisotropic DDK3 filter** to suppress the noise.

Uncertainty estimation: MCMC propagation of the full covariance information (Yang et al., 2024).

Gap-filling: Iterative reconstruction (Forootan et al., 2020).

W3RA water balance model outputs

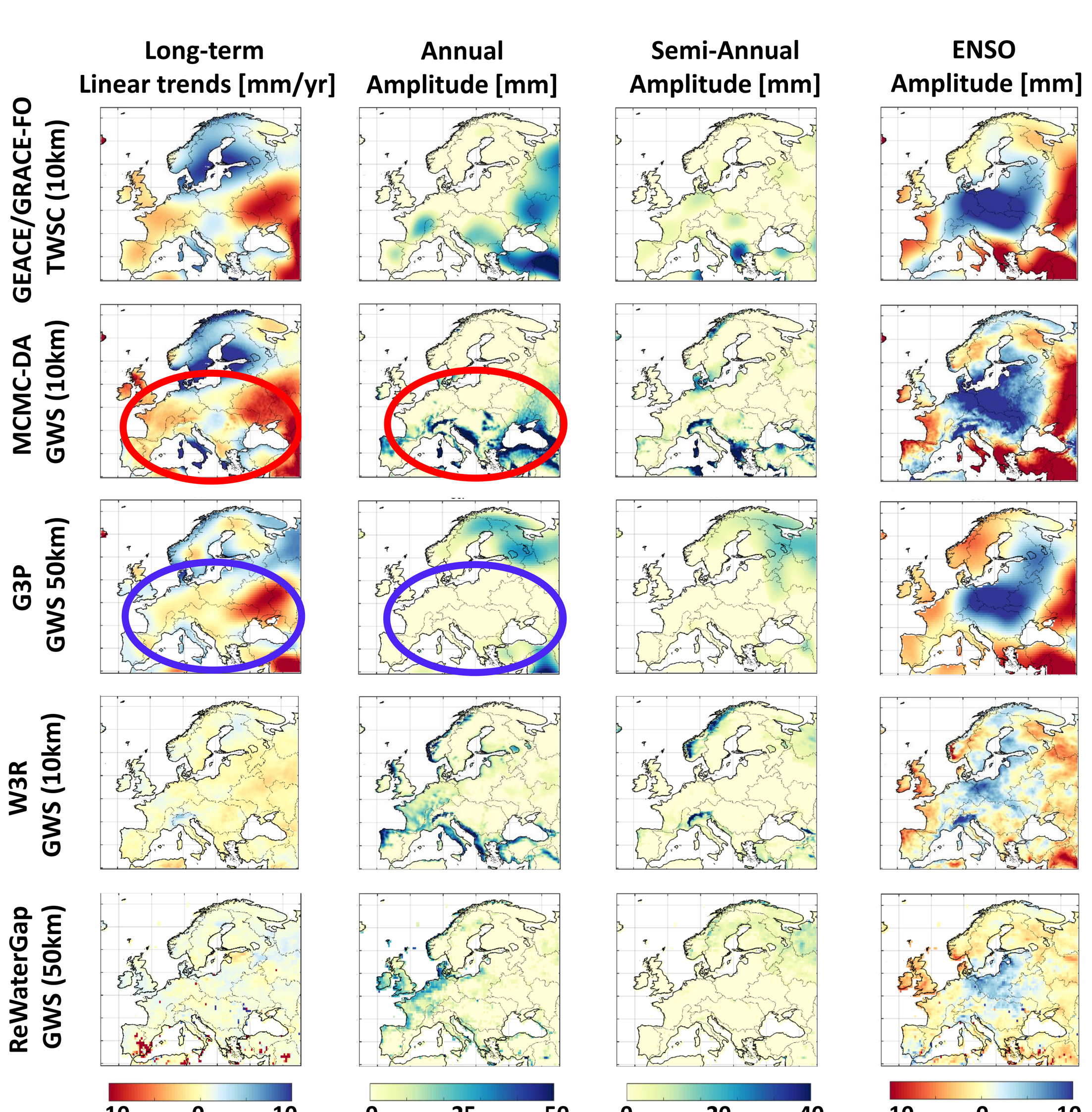


W3RA hydrological components serve as **a priori information** for constraining the individual components of TWS changes in this study.

Meteorological Forcing: Daily averages of ERA5-Land hourly fields are used for: Precipitation, Surface solar radiation downwards, Albedo, 10-meter wind speed. Minimum and maximum temperatures are derived from **ERA5 hourly data** (single-level fields). **Model uncertainty** is estimated by applying a perturbed meteorological forcing approach.

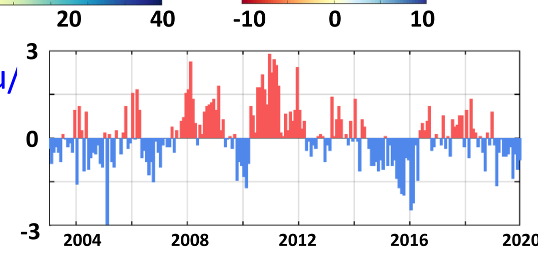
Results

❖ **Evaluation of linear trends, seasonality, and inter-annual signals in Groundwater Storage Changes (GWS)**



❖ **Direct Reduction (G3P**, https://www.g3p.eu/

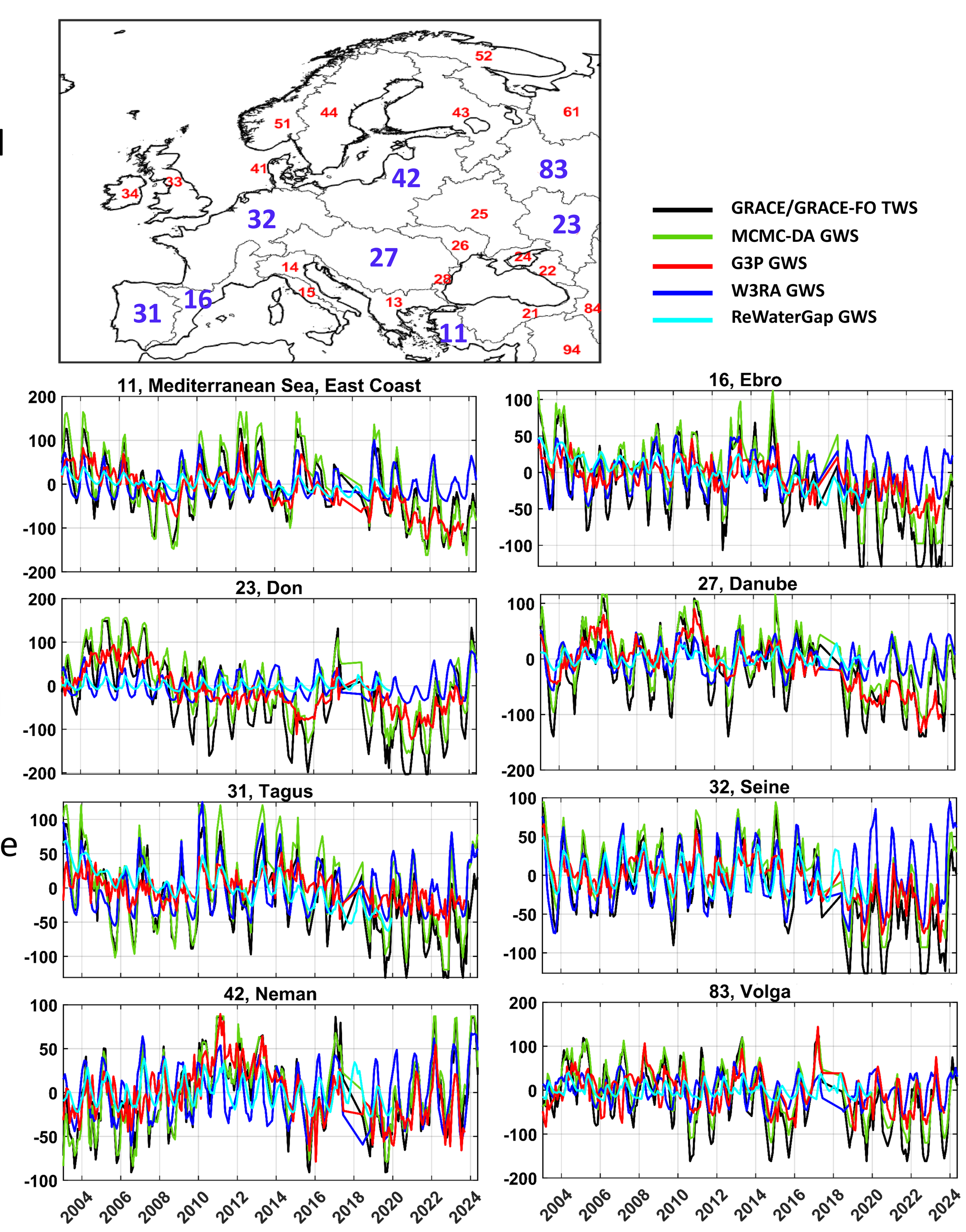
❖ **Bayesian Reduction (MCMC-DA)**
Closer to 10km resolution &
More realistic seasonality



❖ Time period between 2003/04 – 2019/12, limited to the ReWaterGap data (https://doi.org/10.5194/gmd-17-8817-2024)

- **Improving Trends and Variability:**
  MCMC-DA significantly improves the linear trends, seasonality, and interannual signals of the original model outputs relative to GRACE/GRACE-FO observations.
- **Better Seasonal Agreement:**
  Compared to G3P, MCMC-DA shows a closer agreement with GRACE in capturing seasonal variations.
- **Enhanced Spatial Detail:**
  MCMC-DA reveals finer spatial structures at high resolution (10 km) compared to filtered GRACE data and other hydrological models and groundwater product.
- **Stronger ENSO Relationships:**
  The correlation coefficients between the ENSO index and the groundwater ENSO mode increase after merging W3RA outputs with GRACE/GRACE-FO TWSC and ESA CCI Soil Moisture data.
- **Improved Timing of Water Storage Changes:**
  Integrating remote sensing data into W3RA reduces phase differences, leading to a better match in the timing of water storage changes.
- **Enhanced Representation of Slow Processes:**
  The MCMC-DA assimilation improves the representation of slowly evolving hydrological processes, such as hydrological droughts.

❖ **Comparing Basin-Averaged Groundwater Storage Changes [mm]**



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