

Motivation

- ▶ GRACE/-FO observations are crucial for understanding terrestrial water storage (TWS), but limited by coarse resolution (300 km, monthly)
- ▶ The MAGIC constellation (GRACE-C ~2028; ESA NGGM ~2032) promises enhanced spatiotemporal resolution and reduced uncertainty

Research Questions:

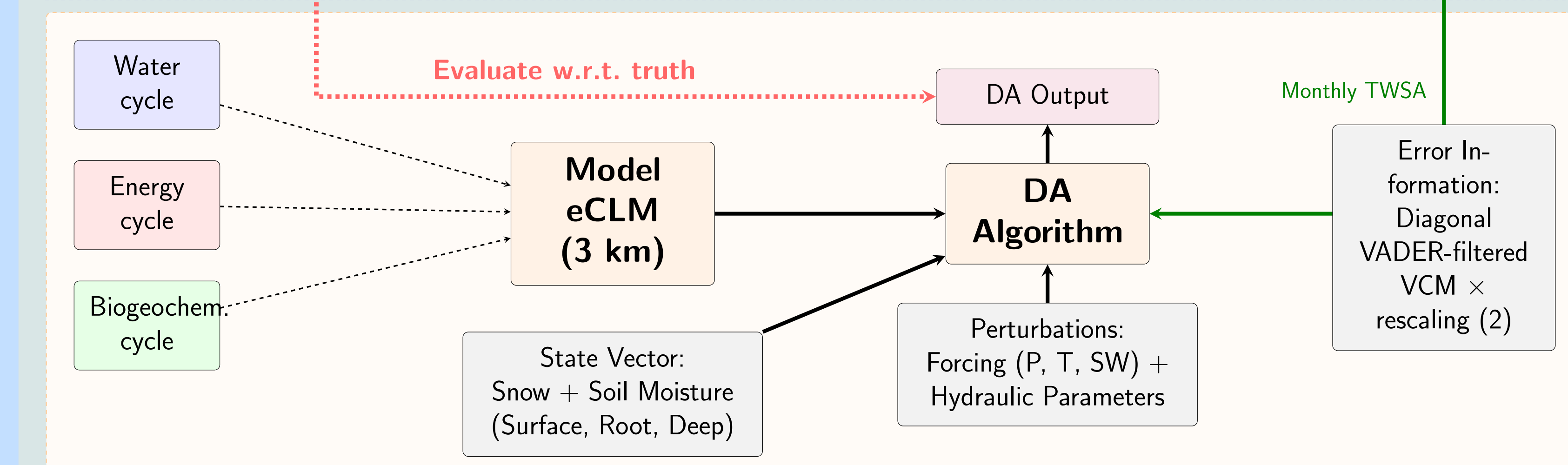
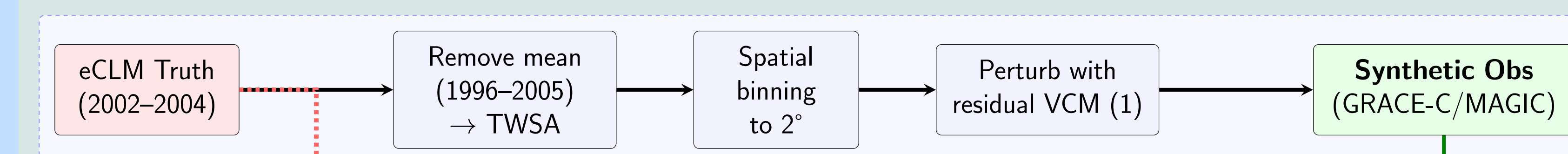
- ▶ How much does MAGIC data assimilation (DA) improve TWS estimates relative to GRACE-C? How are DA-induced improvements distributed across soil depth?
- ▶ To what extent do improvements in the water cycle translate into improvements in carbon and energy fluxes?
- ▶ What are the potential synergies with remote sensing of vegetation and energy fluxes?

Focus regions: Eastern Europe and Iberian Peninsula selected for strong land-atmosphere coupling

Methods: Synthetic Data Assimilation Experiment

Setup: Truth: Deterministic eCLM run (1996–2005); observations generated from 2002–2004, OL and DA run over 1996–1998 (32 members, perturbed forcing and hydraulic parameters). The same climatological mean (1996–2005) is removed during observation generation and from model states in PDAF; remaining differences reflect the drier 2002–2004 climate relative to 1996–1998.

Synthetic Observation Generation



Synthetic Observations (GRACE-C/MAGIC): monthly VCMs (d/o 120) from ESA SING project, based ESM simulations including instrument noise, de-aliasing and ocean tide errors. **Two distinct VCMs per mission:** (1) VADER-filtered **residual VCM** (errors relative to ESM reference, includes signal damping) used to perturb synthetic observations; (2) VADER-filtered **diagonal VCM** with rescaling used in DA framework, simulating the real-world case where no perfect error reference is available.

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Results and Discussion

TWS RMSE Improvement: MAGIC vs. GRACE-C DA

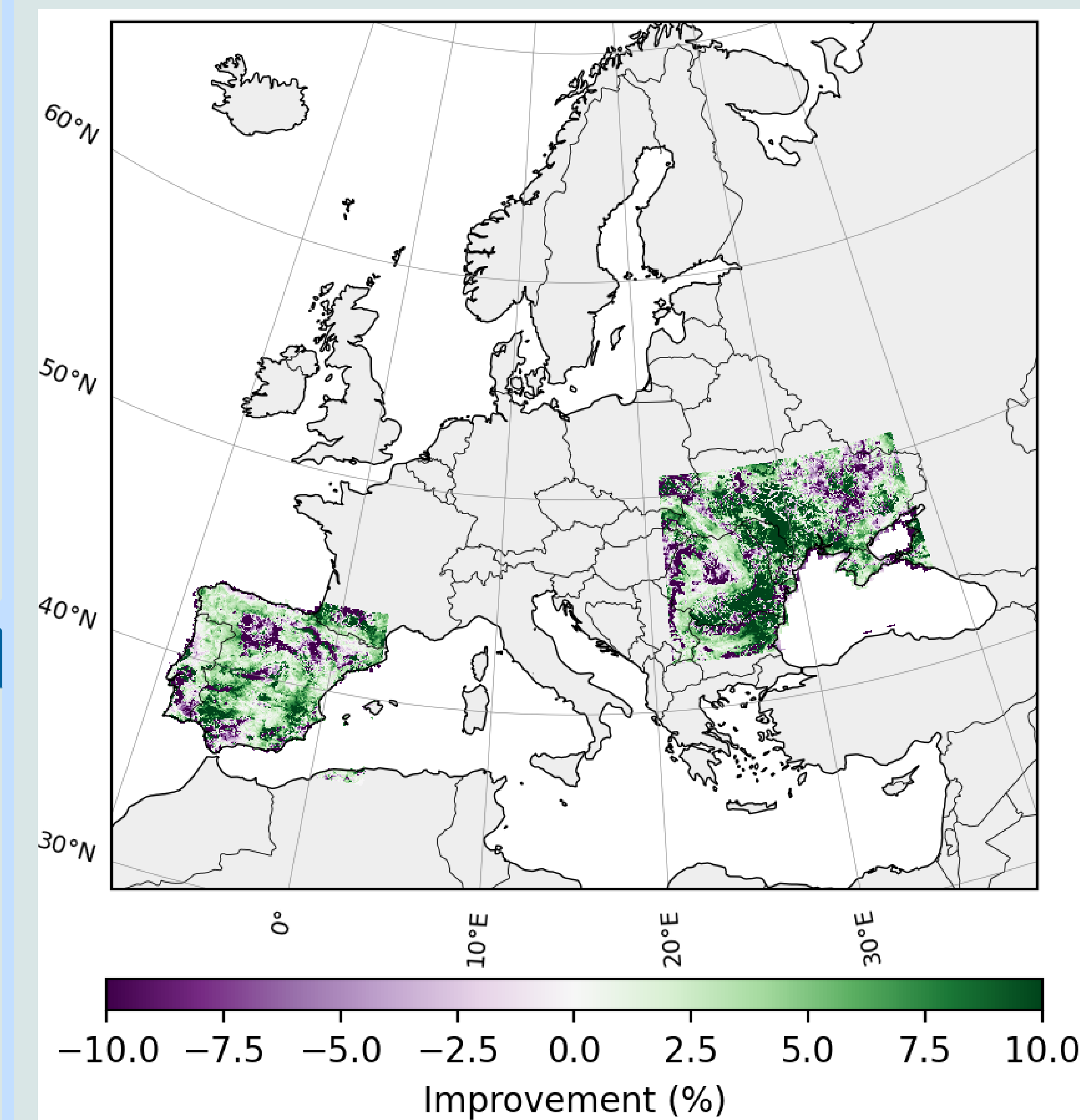


Figure 1: TWS RMSE improvement of MAGIC DA over GRACE-C DA, both w.r.t. truth [%].

RMSE Improvement Through Soil Column (MAGIC vs. OL)

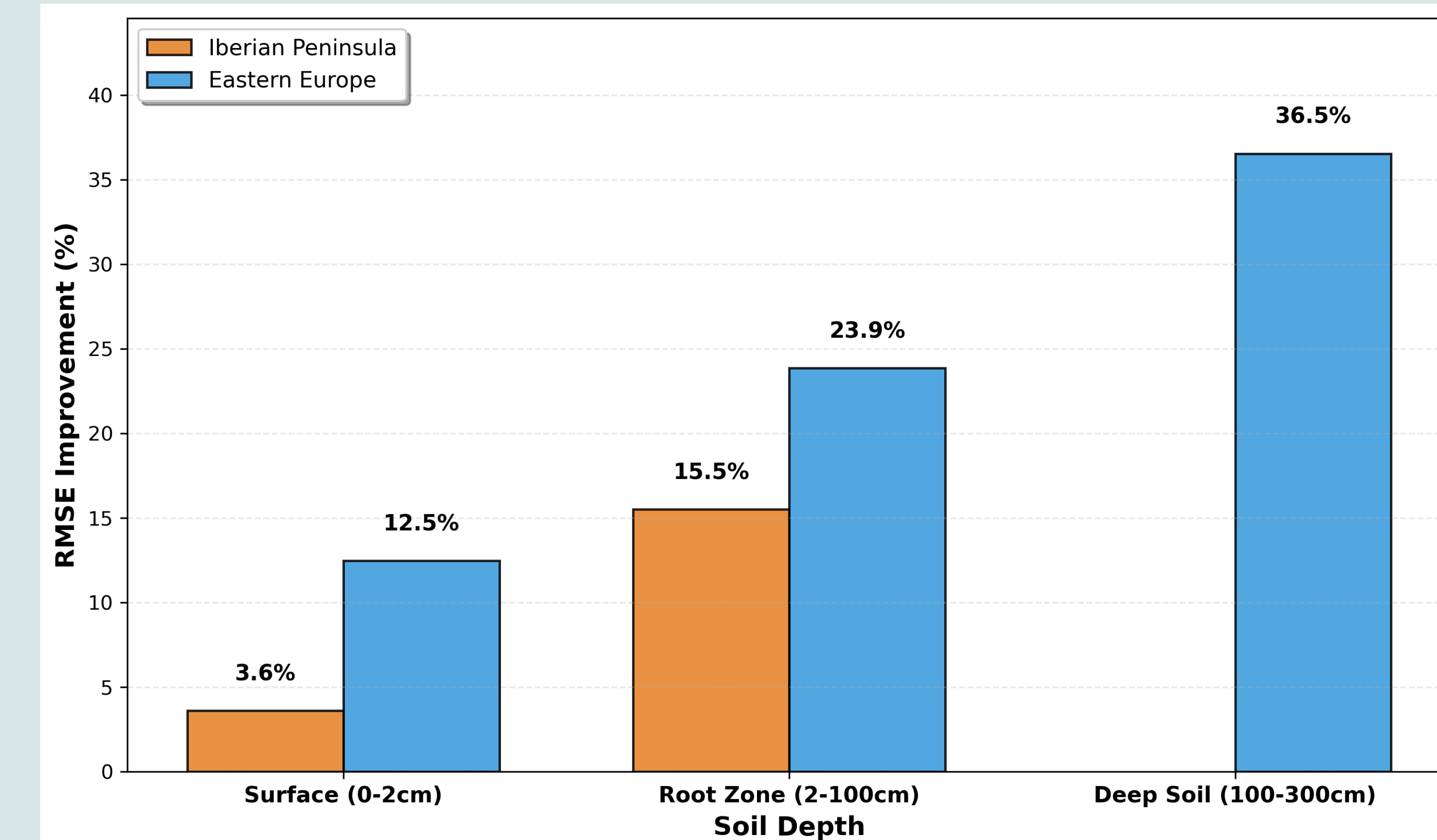


Figure 2: Soil moisture RMSE improvement of MAGIC DA over OL, w.r.t. truth. Eastern Europe: Surface (12.5%) → Root Zone (23.9%) → Deep Soil (36.5%).

- ▶ MAGIC outperforms GRACE-C in majority of domain, largest gains in Eastern Europe
- ▶ RMSE improvements increase progressively with soil depth
- ▶ Regional differences: Eastern Europe (TWS OL RMSE: 127.5 mm) benefits more than Iberian Peninsula (79.5 mm)

Water-Carbon-Energy Coupling: Iberian Peninsula

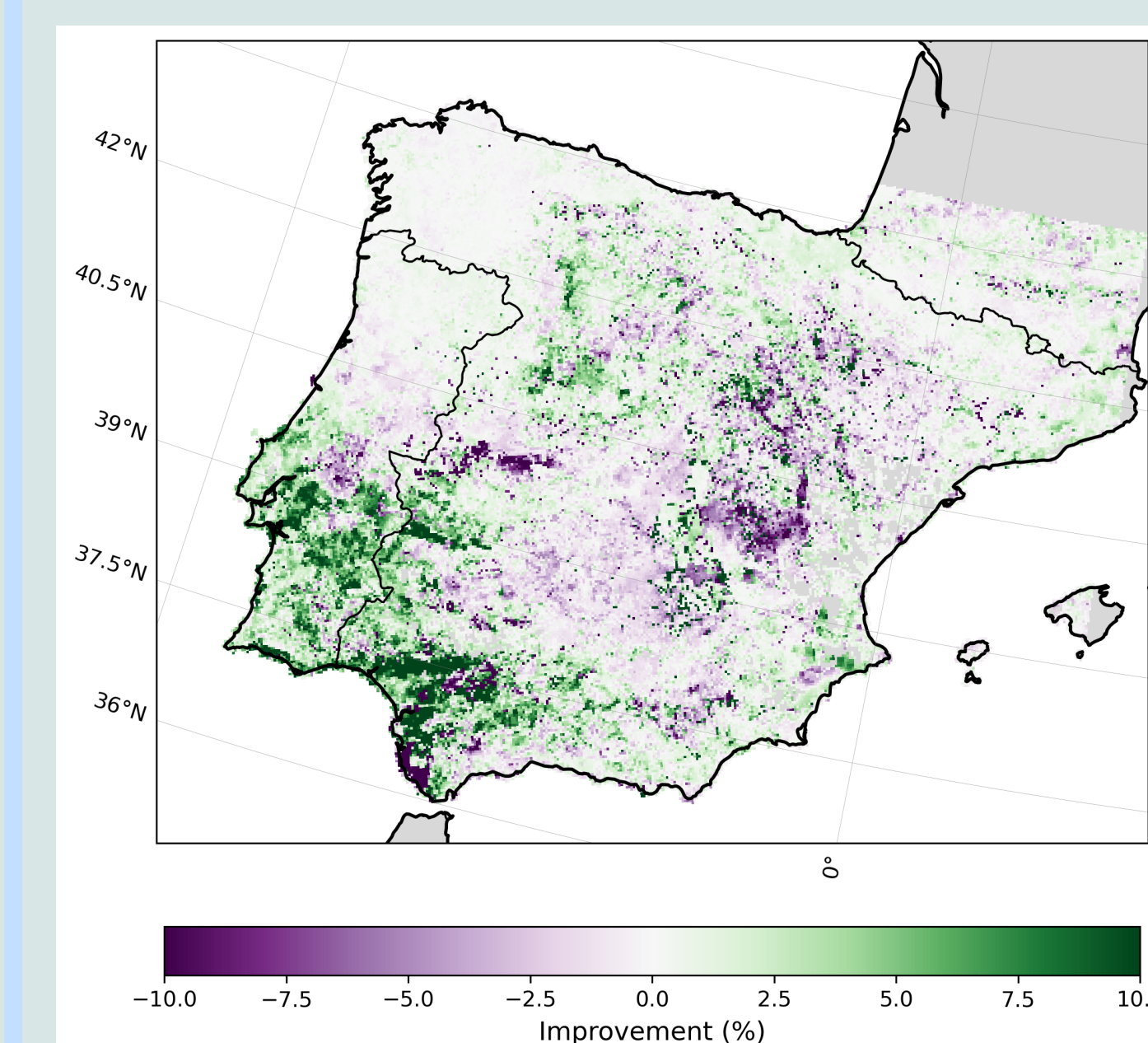


Figure 3: Ecosystem Water Use Efficiency (EWUE = GPP/ET) RMSE improvement: MAGIC vs. GRACE-C DA [%].

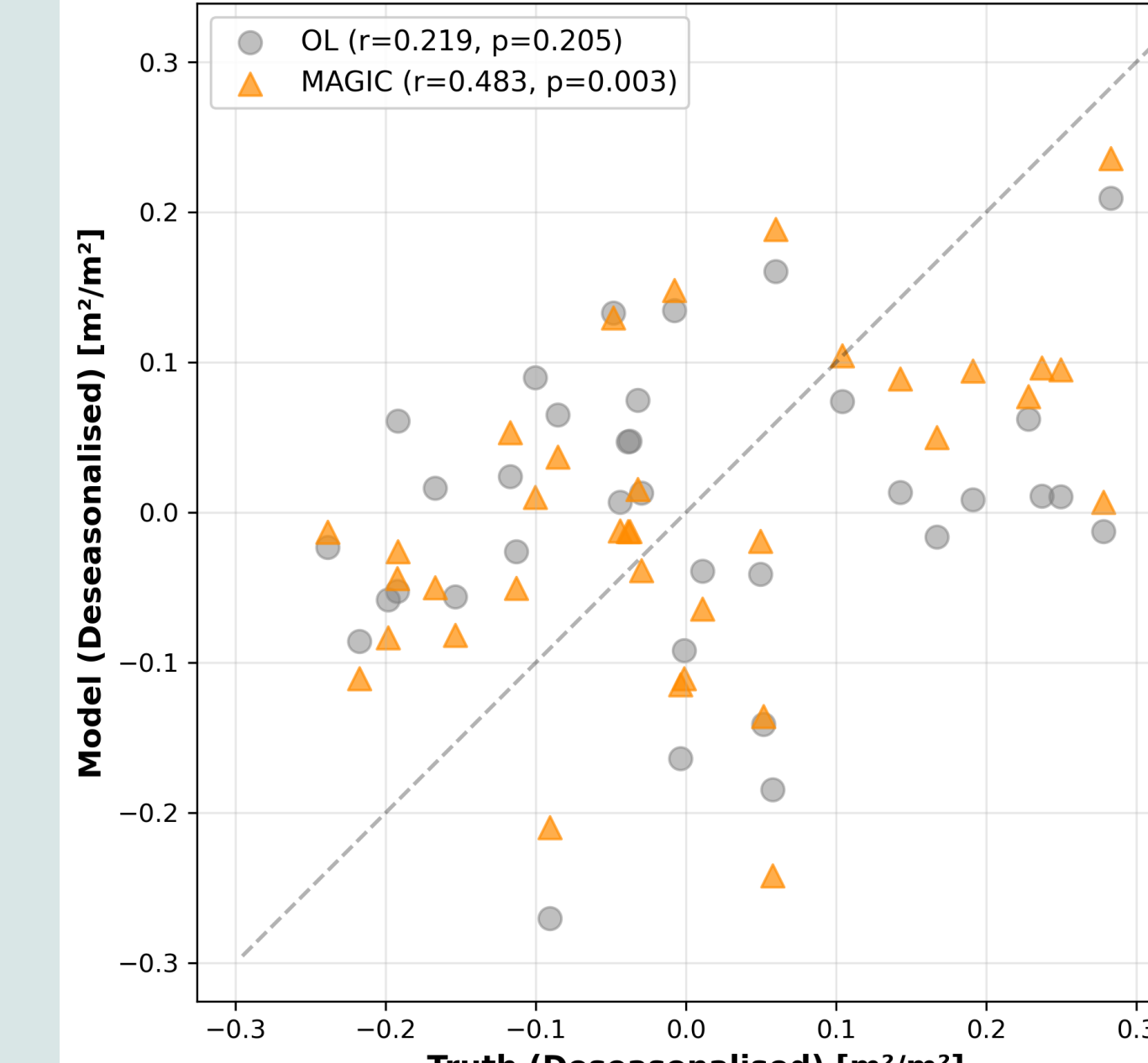


Figure 4: Deseasonalised Leaf Area Index (LAI) temporal correlation with truth.

- ▶ LAI dynamics improve significantly ($r: 0.22 \rightarrow 0.48, p < 0.01$)
- ▶ EWUE: improvements in Atlantic-influenced west, degradation in continental interior, reflecting complex ecosystem responses

Conclusion and Outlook

Conclusions

- ▶ RMSE improvement (MAGIC vs. OL, w.r.t. truth) increases with depth (12.5% → 36.5%), reflecting larger storage capacity and reduced surface-driven variability at depth
- ▶ MAGIC DA improves water states and enhances vegetation dynamics in the water-limited Iberian Peninsula, while carbon-water responses (EWUE) remain spatially heterogeneous

Outlook

- ▶ Multivariate DA: joint assimilation of TWS and vegetation (LAI/SIF) to directly constrain coupling
- ▶ Quantify coupling strength and memory effects across multiple seasons