Benefit of multi-pair quantum satellite gravity missions in Earth science applications

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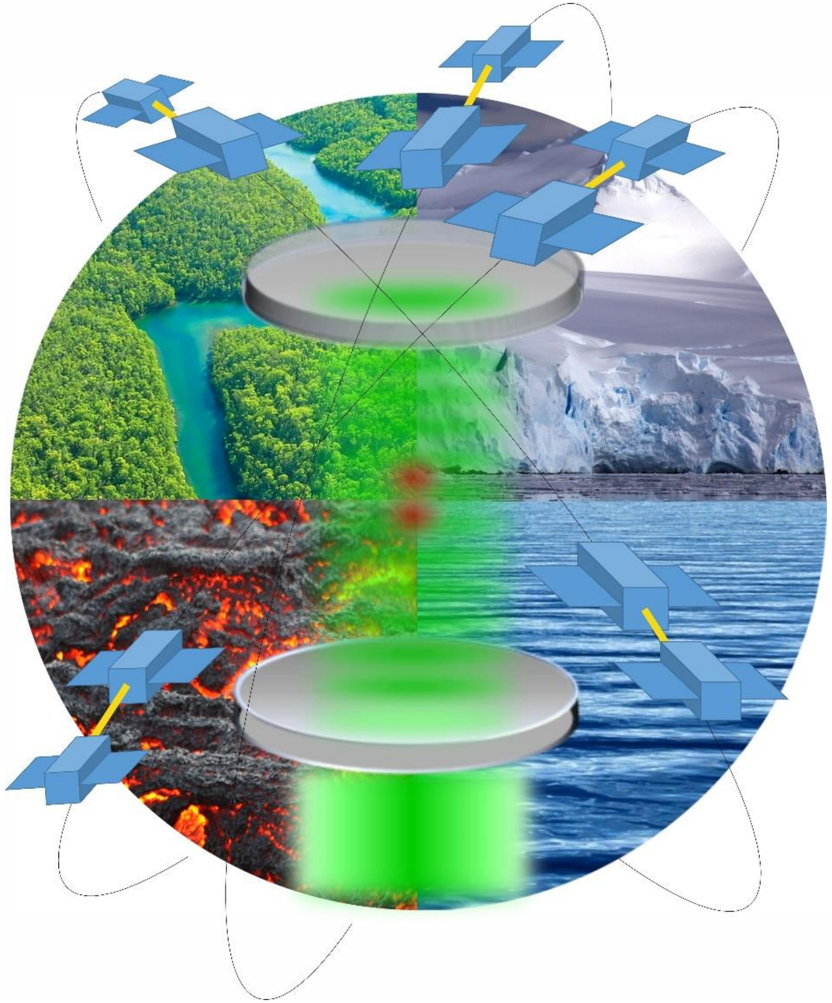


Context

- **GRACE and GRACE-FO have provided unique data and enabled new directions and various "firsts" in hydrology, ocean and sealevel, climate science, solid Earth, and many other fields**

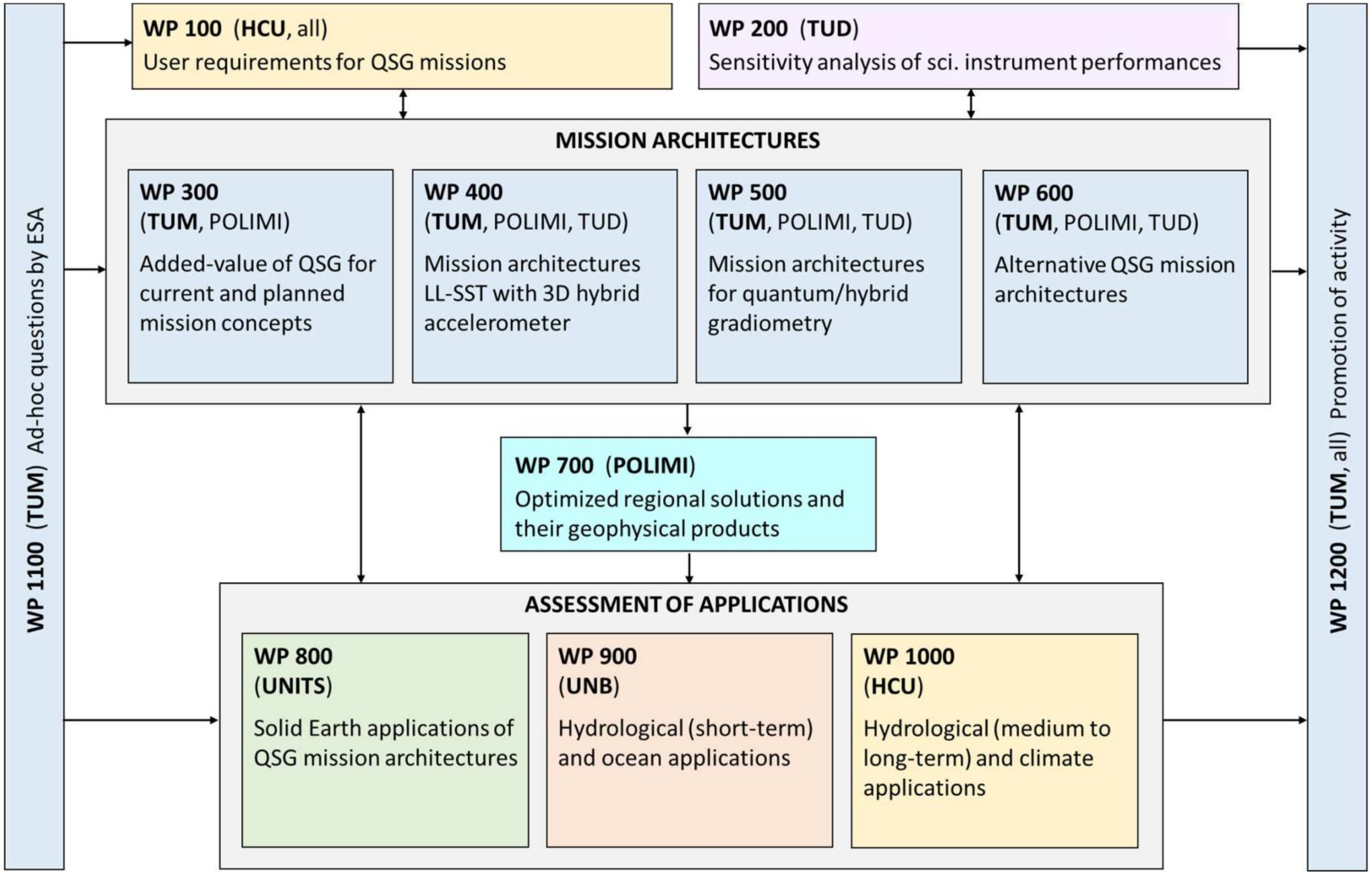
- **Various applications require data products of higher spatial and temporal resolution with lower uncertainty (cf. ESA QSG4EMT user questionnaire presented by Annette Eicker and Christina Strohmenger in Assissi and subsequent meetings)**
- **Obstacle to improving resolution seem background models and instrument noise**

- **GRACE-C and NGGM (Phase B1 approved) will fly as a two-pair constellation in overlap period (MAGIC)**
- **Quantum instrumentation studies suggest that cold-atom interferometer (CAI) instrument, potentially as gradiometer, could be flown with laser ranging instrument (LRI) in the future**

- **<u>What would be the benefit of such scenarios in realistic Earth science applications?</u>**

- **Assessed in ESA study Quantum Space Gravimetry for monitoring Earth's Mass Transport (QSG4EMT)**

Project architecture and study logic



Technical background for what will be discussed in the following

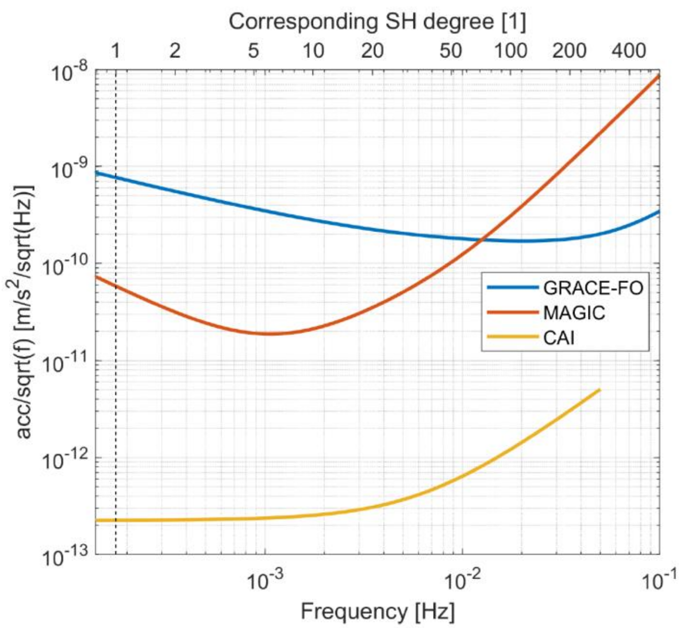
Single-/Multiple-pair scenarios

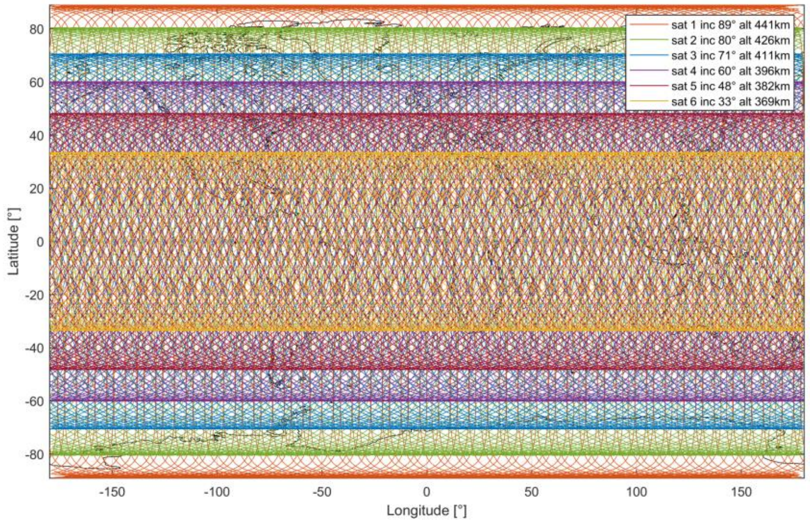
- **GRACE-FO and MAGIC: MAGIC/NGGM threshold requirements (ESA), Heller-Kaikov et al., 2023**
- **CAI3 and CAI6 scenario: up to 6 pairs at different inclination, optimized orbital planes and altitudes (370-440 km)**
- **Instrument errors: improved LRI (2040) and CAI, Zingerle et al., 2024, Encarnacao et al. (2024)**

Dealiasing background model errors: updated ESAESM Shihora et al. (2024)

Retrieval TUM and POLIMI: 12 years of unconstrained weekly d/o 120 solutions

"Monthly solutions" in the following: accumulated weekly





Two ways of error simulation in applications

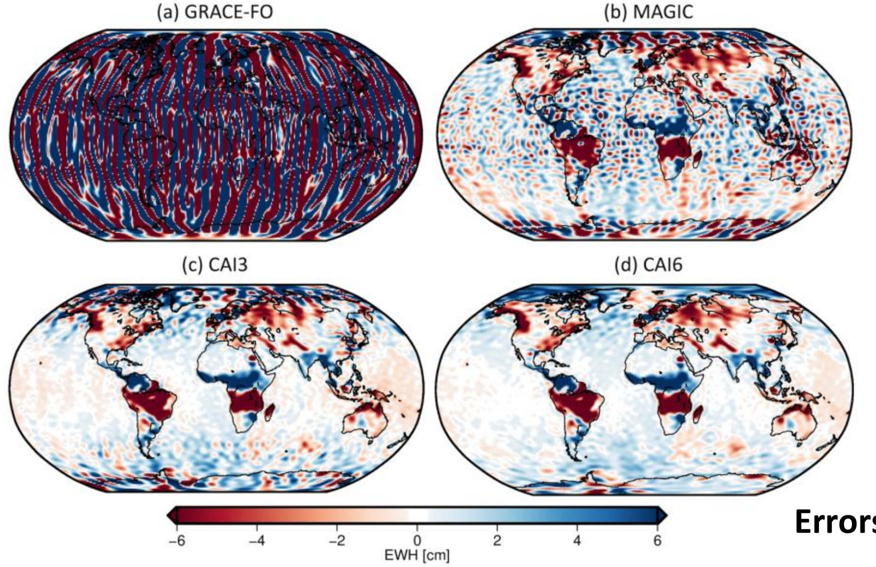
- **direct retrieval/comparison of variables that were explicitly modelled in ESAESM, i.e. TWSA, ocean mass**
- **estimating a positive definite variance covariance matrix and use in applications (e.g. data assimilation, DA)**

Hydrology – basin-averaged TWSA

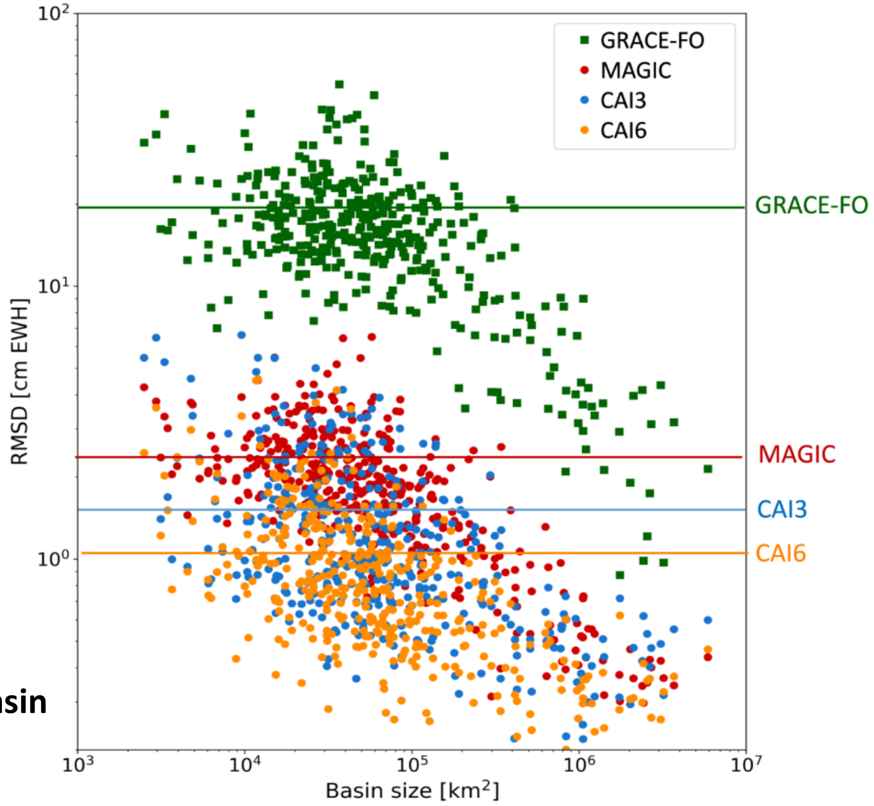
Provide constraints for assessment of drought and flood conditions, constrain terrestrial/atmospheric water budget, solve for groundwater anomalies, …

Experiment with ESAESM truth for 400 larges river basins

- **Weekly solutions**
- **Same DDK5-filter and basin averages**



Errors weekly solution



RMSD basin avg. vs. size of basin

Preliminary findings

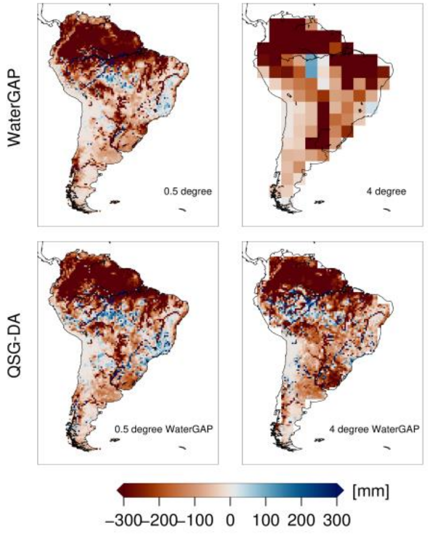
- **Clear benefit for multiple-pair (MAGIC and CAI) over single-pair (GRACE-FO) scenario**
- **70% thresholds (see figure): GRACE-FO 19.5cm, MAGIC 2.3cm, CAI3 1.5cm, CAI6 1.0cm**

Hydrology – assimilation in global models

Provide most realistic picture of water storages and fluxes at model resolution (GHM mostly 0,5°)

Observation System Simulation Experiment

- Assimilation of monthly DDK-filtered TWSA maps in WaterGAP, v2.2e
- Ensemble Kalman filter, WaterGAP as synthetic truth
- Similar to Gerdener et al. (2023), GLWS2.0 with real GRACE/-FO data
- WaterGAP forcing/model errors as in Gerdener et al. (2023)

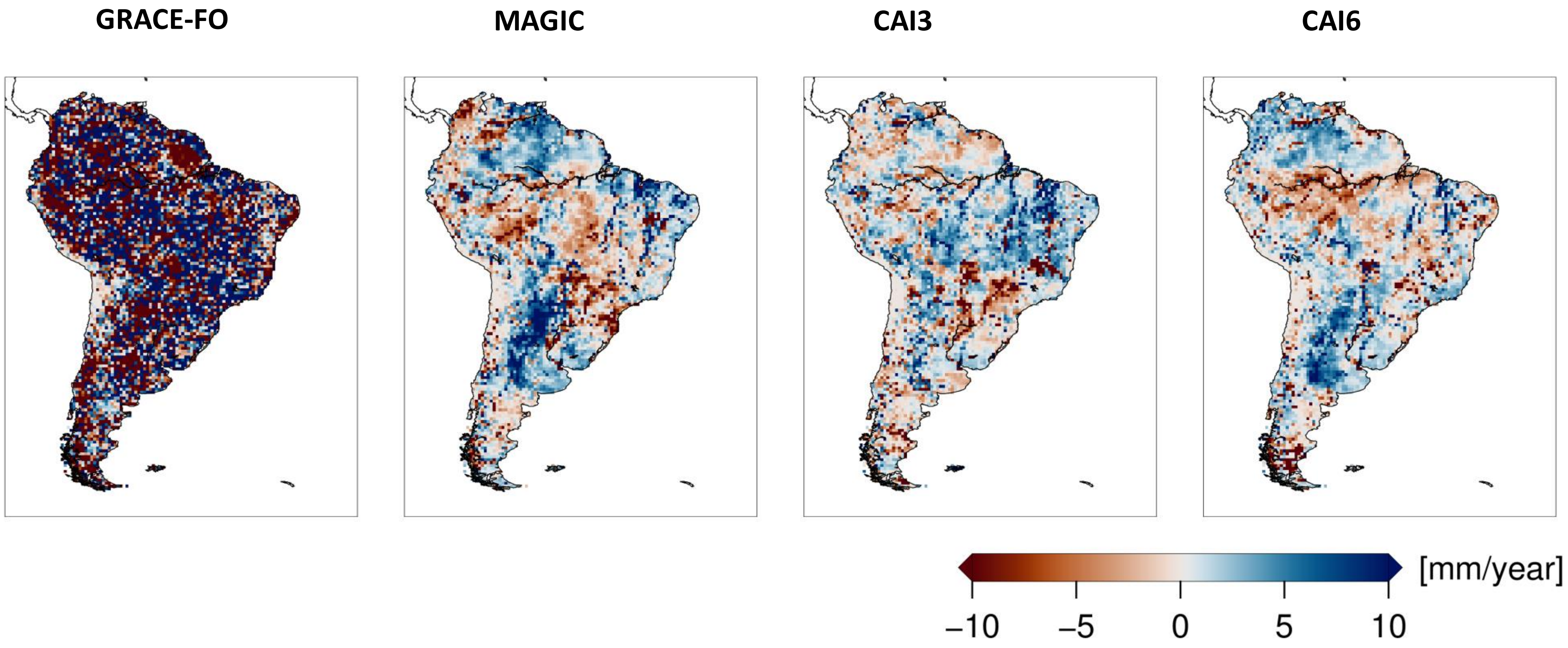


All multiple-pair scenarios allow DA of TWSA maps at native 0.5° GHM resolution (not possible for real GRACE-FO data, 30% worse in simulation)

Preliminary findings

- Clear benefit for multiple-pair (MAGIC and CAI) over single-pair (GRACE-FO) scenario
- Trends 2003-2019
  - After DA, TWSA uncertainty (RMSD) for MP at 50 km corresponds to simulated GRACE-FO DA uncertainty at 300 km scale and better
  - 50 km South America: GRACE-FO 44m/a, MAGIC 16mm/a, CAI3 and CAI6 13 mm/a
- Annual / semi-annual amplitude and phase
  - After DA, TWSA uncertainty for MP at 100 km smaller than for GRACE-FO DA at 300 km scale.
- Consistent improvements also for groundwater storage anomalies, mixed results for surface water and soil moisture
- Model uncertainty too conservative?
- DA methods may need adaptation for aliasing errors

Hydrology – assimilation in global models



Differences of linear TWSA trends [mm/year] from assimilation of WaterGAP TWSA with empirical uncertainties w.r.t. WaterGAP (truth) simulations

Hydrology – assimilation in regional models

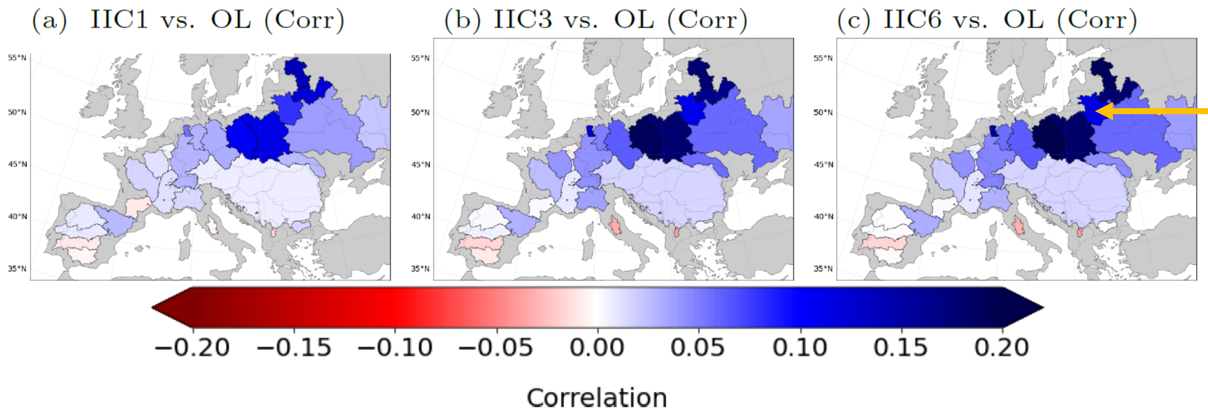
Land surface models simulate coupled water, energy and biogeochemical cycles, higher resolution than GHMs

Observation System Simulation Experiment

- Assimilation of monthly DDK-filtered TWSA maps in CLM3.5 (12 km, 1-h resolution) over Europe (CORDEX)
- Part of TerrSysMP-PDAF coupled ESM (COSMO/ICON, CLM, Parflow), Shrestha et al. (2014), used also in CRC DETECT, also SSM, LST DA
- Synthetic truth: CLM5 model run (systematically different over Eastern Europe due to snow representation problem in CLM3.5)

Preliminary findings

- DA leads to improvement in terms of RMSD and correlation at catchment scale over Europe
- DA improves the representation of the annual cycle and extremes, but cannot completely correct the trend
- Scenario CAI6 performs significantly better than simulated GRACE-FO and outperforms MAGIC and CAI3 over most catchments
- Errors may be dominated by imperfect model dynamics



Example: Narva basin (56,000km²) timeseries errors

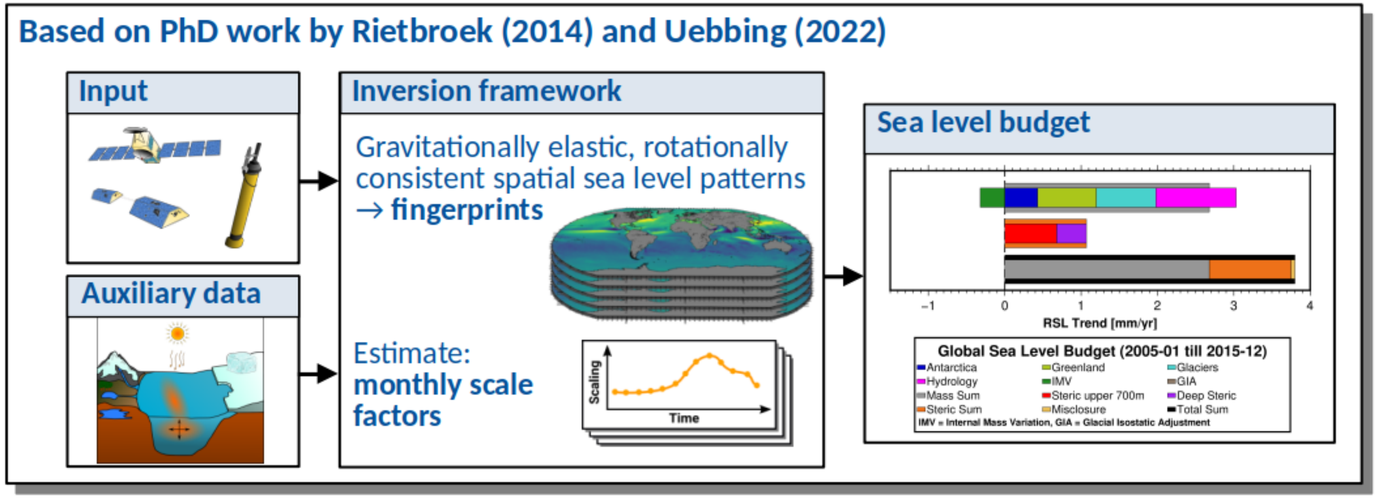
- CLM3.5 5-6cm
- CLM3.5 w GRACE-FO DA 4cm
- CLM3.5 w CAI3/6 DA 3cm

Ocean mass – partitioning of altimetric sea level

Partition sea level change into contributors glacier and ice sheet mass loss, land hydrology, steric change, etc.

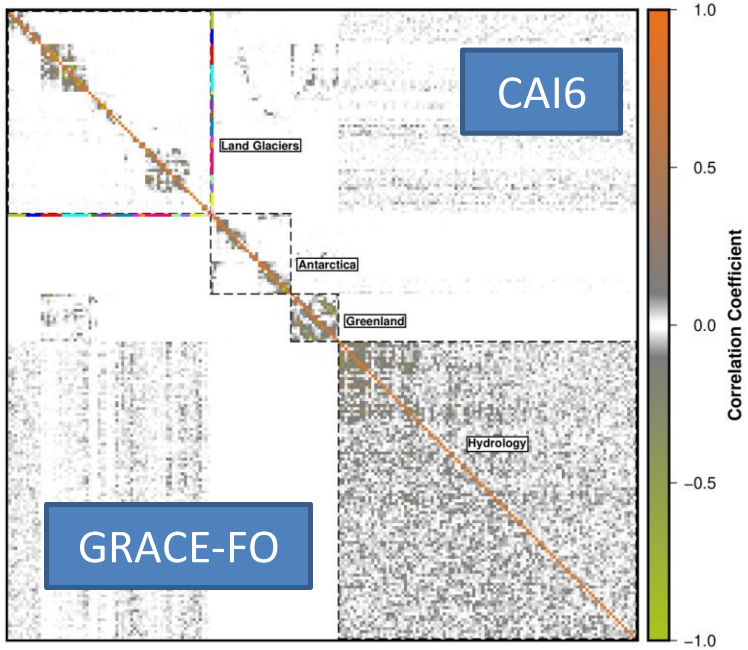
Least-squares inversion framework Rietbroek et al. (2016)

- Combination of SHCs and altimetry at normal equations level, solving for contributions in fingerprint space
- Error propagation experiment with replacing real GRACE/-FO NEQs by inverse scenario VCE and Jason-1/-2/-3 errors



Preliminary findings

- At global scale, ocean mass is already well-determined
- MP scenarios reduce error correlation between neighboring glacier systems, Greenland/Antarctica basins, … this is hypothesized to improve spatial partitioning
- Very sensitive w.r.t. error modelling



Ocean mass – regional study (East China Sea)

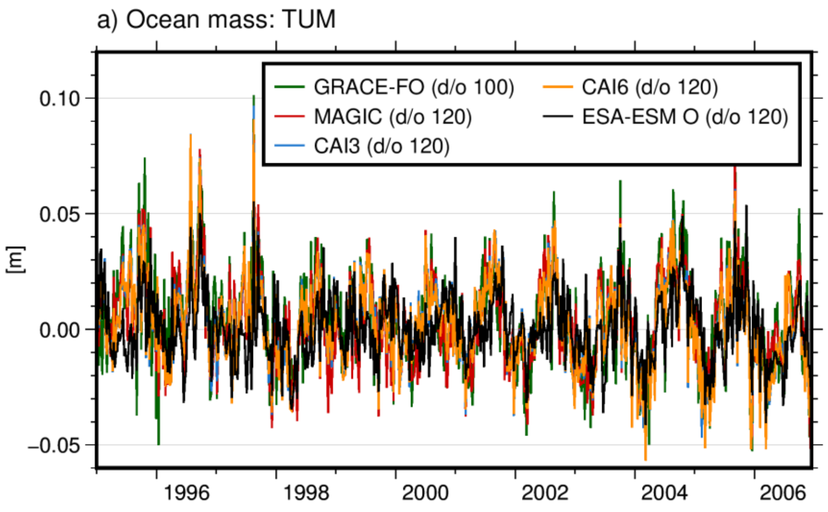
Retrieval of ocean mass allows to derive ocean warming and salinity redistribution; challenging for regional seas

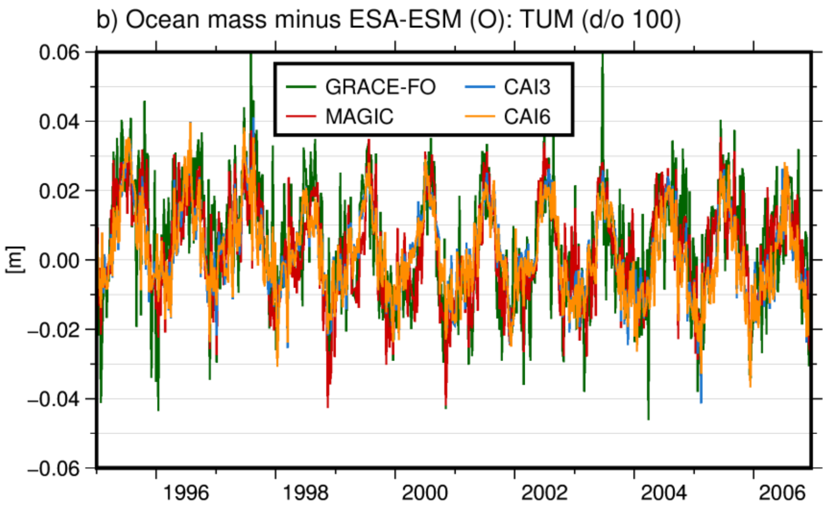
Experiment with ESAESM truth for East China Sea

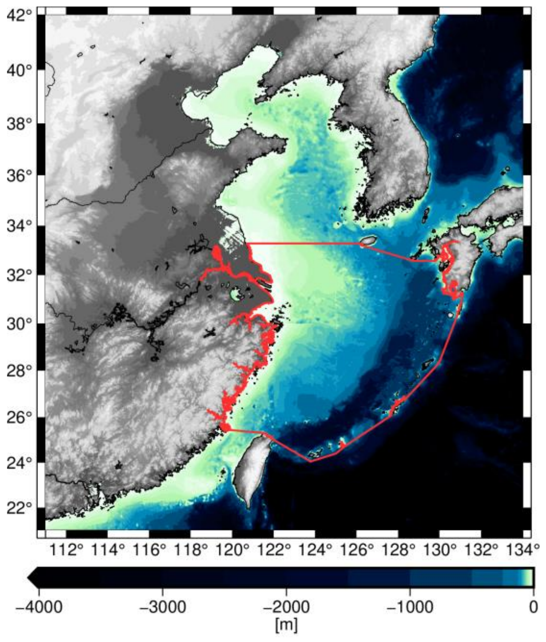
- 770.000 km², complex ocean current system, mostly shallow bathymetry, large sediment inflow
- Hydrological aliasing

Preliminary findings

- All MP scenarios improve over GRACE-FO simulation, as expected
- Timeseries mass errors 1.5/1.1/0.7/0.7 cm (against ESAESM), this corresponds to 2.3/0.9/0.6/0.7 cm (scaled formal errors)
- Differences TUM vs POLIMI regional solution are below differences w.r.t. truth





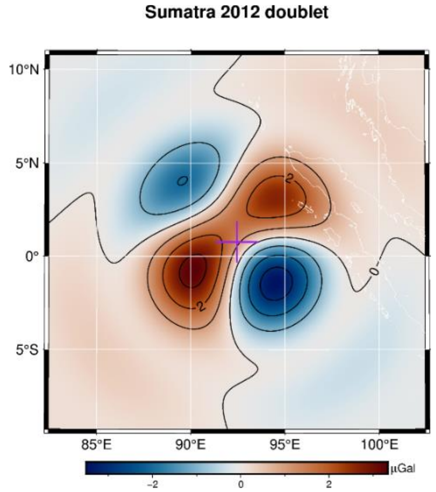


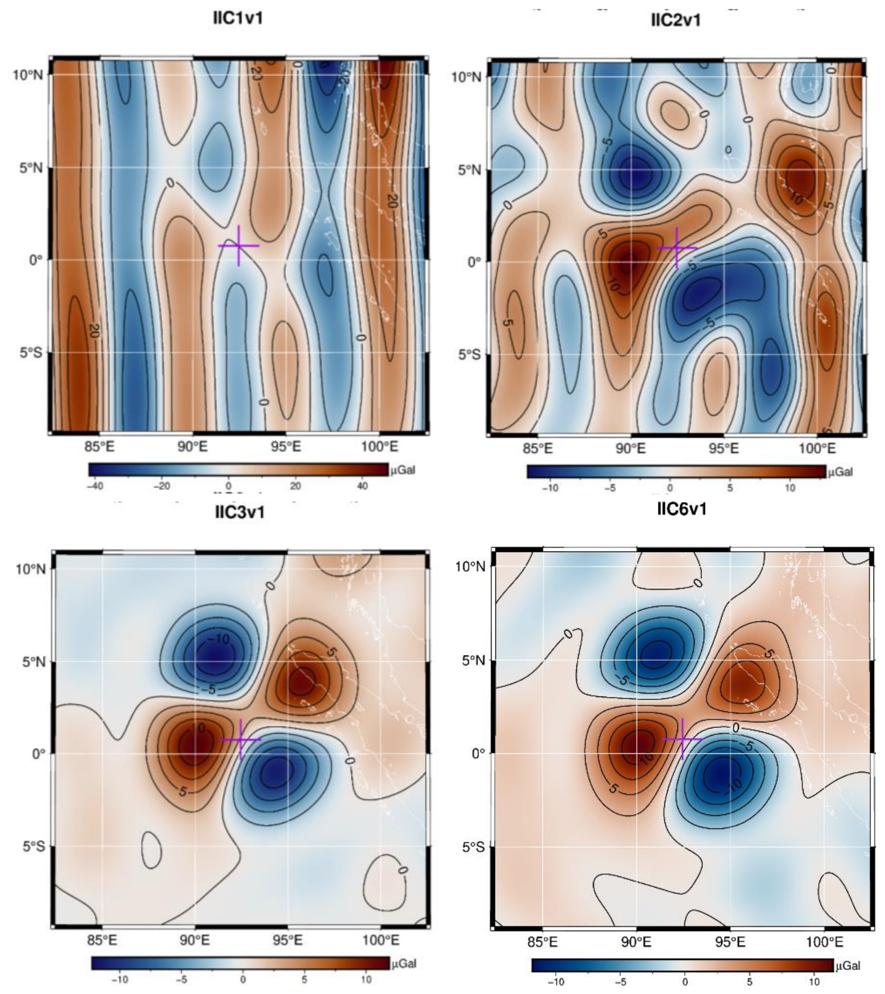
Solid Earth Applications

Improved sensitivity of constellations opens perspective of new services linked to:

Tectonic activity: earthquakes co-postseismic gravity fault movement. Submarine Volcanos silent eruptions

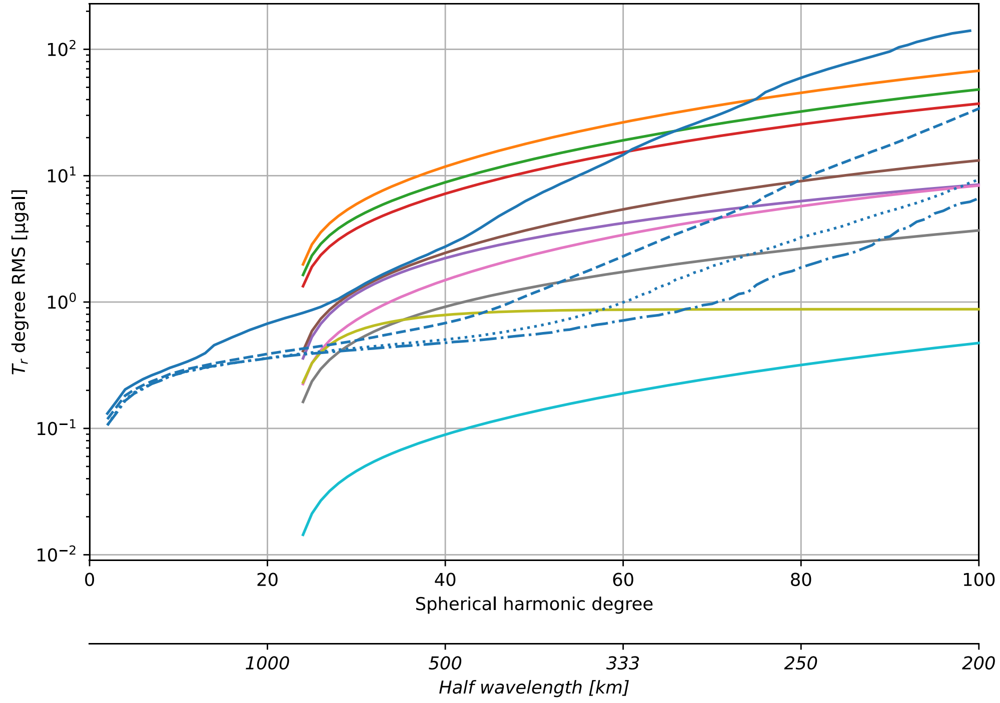
Difference of modelled gravity fields, weekly solutions: week after minus week before earthquake

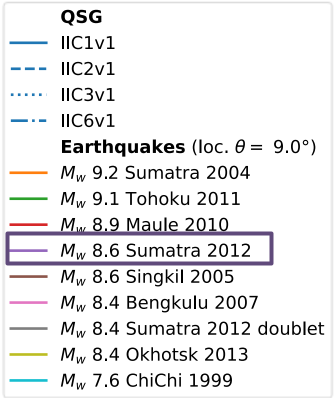




Earthquakes detection

Co-seismic + 1 week post-seismic against 1-week solutions



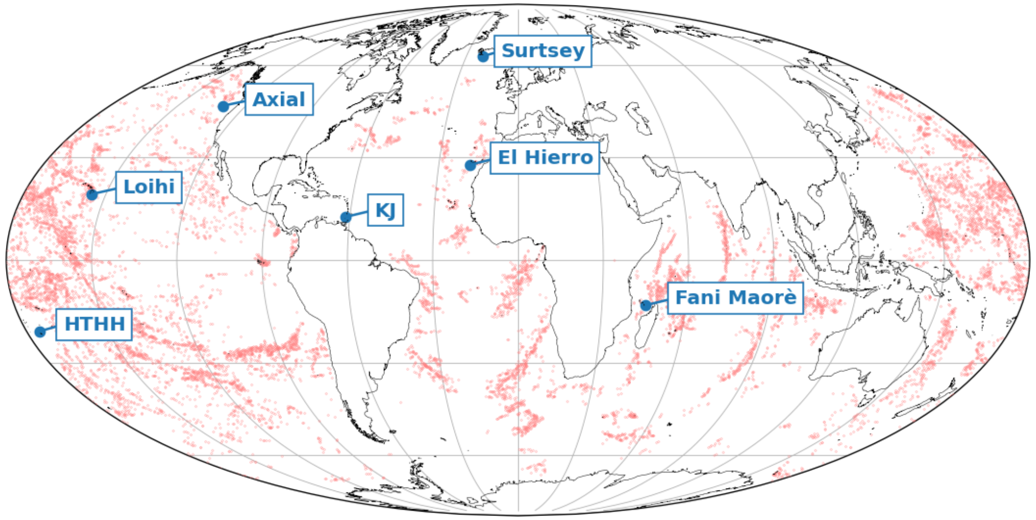


Signal: Coseismic deformation + 7 days post-seismic relaxation
Retrieval error curves: 7 day solutions. Cumulative spectral curves

Message:
The earthquake is below noise with IIC1 (GRACE-like).
The EQ starts to be seen with IIC2 (MAGIC-like).

Solid Earth Applications

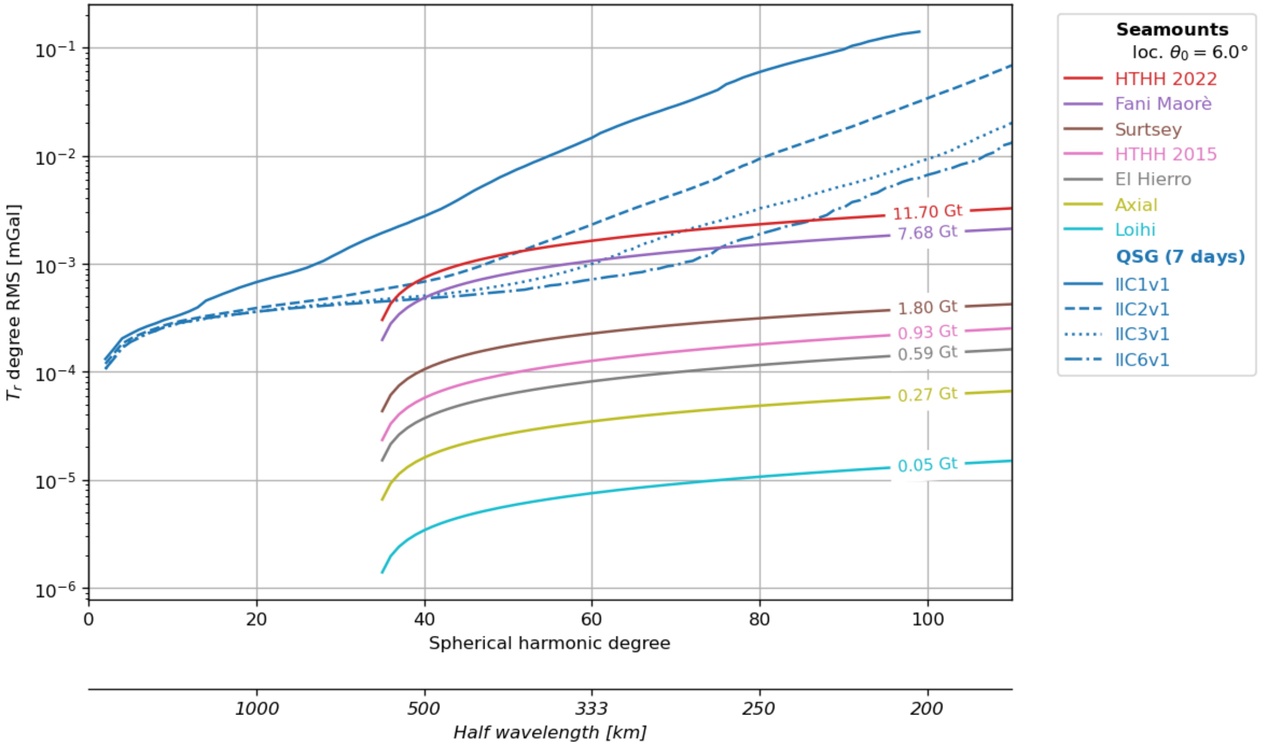
Deep seamount eruptions remain undetected when not explosive.
Example: Fani Maorè volcano offshore Mayotte volcano showed seismic swarms and deformation on Mayotte island. No explosion, but grew 820 m high in 2018-2019. Created uncharted bathymetry



- Wessel P, Sandwell D, Kim S-S (2010) The Global Seamount Census. Oceanography 23:24–33.

- seamount eruptions: mass change estimate and spectral amplitude of gravity signal shown to the right
(Braitenberg & Pastorutti, 2024, Surveys in Geophysics)

Cumulative spectral noise and signal curves



Message:
Mass change of Fani Maorè estimated with 7.7 Gt.
Can be detected with latency of one week with three or six couples

Benefit of multi-pair quantum satellite gravity missions in Earth science applications

Preliminary findings

- Clear benefit multi-pair (MAGIC, CAI3/6) scenarios over GRACE/-FO. Greatest impact is step from polar single to MAGIC double-pair constellation.
- Also in variables derived in combination with models/other EO data (e.g. groundwater storage change)
- Benefit CAI3/6 over MAGIC scenario, but limited in some applications
- Limited by background model errors. Scale of relative improvement diminishes with postprocessing/analysis steps
- Different from GRACE/-FO, for MAGIC and quantum scenarios we can assimilate TWSA maps at native 0,5° resolution of WaterGAP GHM, due to improved resolution of these missions

Limitations of this assessment study

- Background model error realism
- Limitations in simulation sample size and variance-covariance matrix representation
- Complex applications depend on hydrology model error assumptions, radar altimetry errors, we used today's errors here
- Assimilation/inversion schemes tuned to GRACE/-FO over several years