# Multi-decadal Satellite Gravity Mission Simulations Comparing Resolving Capabilities of a Long-term Trend in the Global Ocean Heat Content

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EGU General Assembly 2023
EGU23-8590
Session G3.1 (X2.56)

## 1. Measuring global ocean heat content as a proxi for earth energy imbalance

- Earth Energy Imbalance (**EEI**) at the top of the atmosphere causes energy to accumulate in the Earth's system.
- EEI has a small magnitude (0.5-1 Wm$^{-2}$) compared to the in- and out going Energy (~340 Wm$^{-2}$).
- Measuring EEI is difficult, but an accuracy of < 0.1 Wm$^{-2}$ is necessary to better understand our warming climate. *[1]*
- Oceans absorb most of the Energy imbalance (>90%).
- Changes in Ocean Heat Content (**OHC**) represents good proxy for EEI.
- Space geodetic techniques allow global measurements of the thermal extension of the oceans using the Sea Level (**SL**) budget equation (Eq.1).

(Eq.1) $$\Delta SL_{total} = \Delta SL_{mass} + \Delta SL_{thermo} + \Delta SL_{halo}$$

- Globally the change in salinity in the oceans in negligible, therefore, Eq.1 can be simplified to get the thermosteric SL change

(Eq.2) $$\Delta SL_{thermo} = \Delta SL_{total} - \Delta SL_{mass}$$

- With an expansion coefficient ($\varepsilon$) changes in OHC can be derived (Eq.3).

(Eq.3) $$\Delta OHC = \frac{\Delta SL_{thermo}}{\varepsilon}$$

$\Delta SL_{total}$: Change of total Sea Level (SL) change
$\Delta SL_{thermo}$: Thermal expansion component of SL change
$\Delta SL_{mass}$: Mass component of SL change
$\Delta SL_{halo}$: halosteric component of SL change

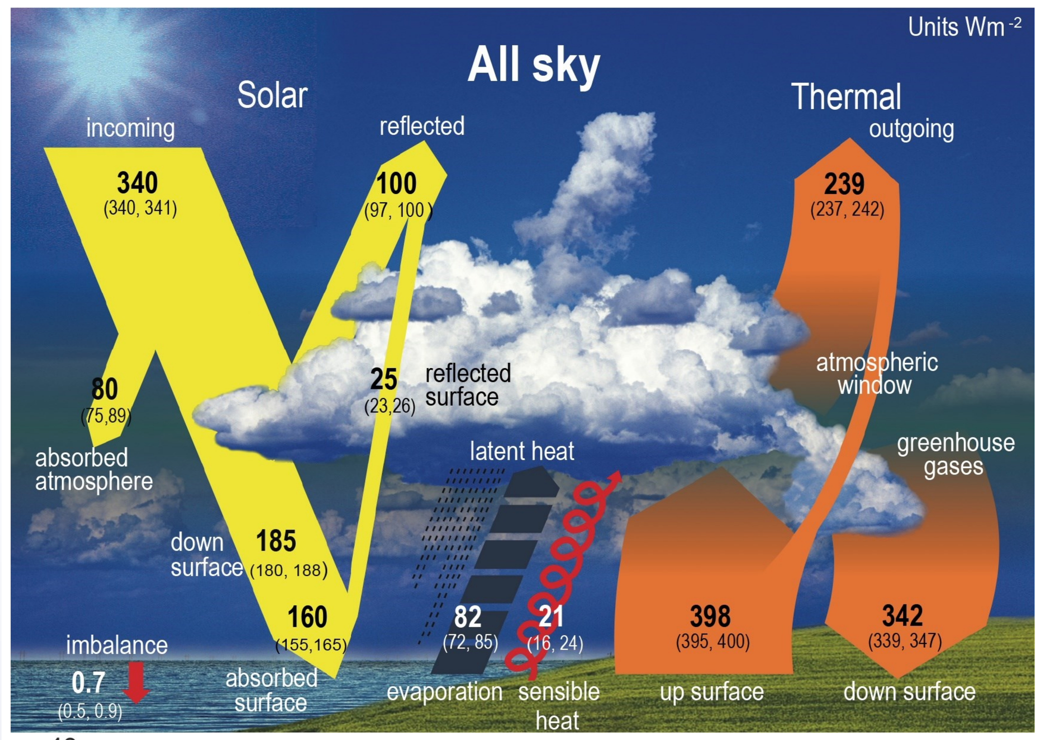


**Fig. 1**: Global energy budget of the Earth beginning of 21st century. The magnitude of the globally averaged components is given in Wm$^{-2}$ (from Forster et al. 2021).

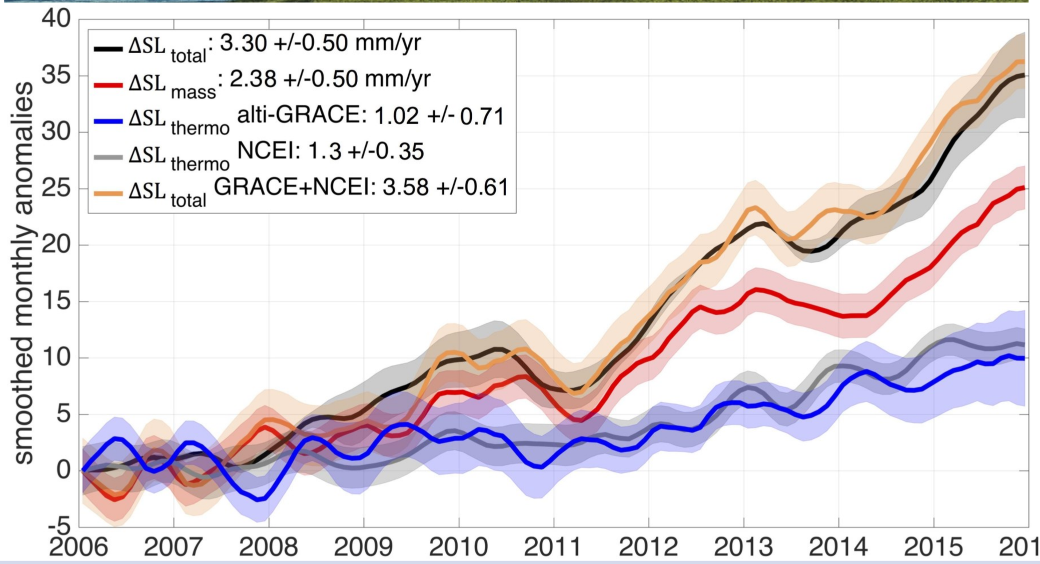


**Fig. 2**: Global mean anomalies of global mean sea level, including $\Delta SL_{total}$ in black, and its components ($\Delta SL_{mass}$) in red and $\Delta SL_{thermo}$ in blue (from *[2]*).

## 2. Measuring ocean heat content with space geodetic techniques

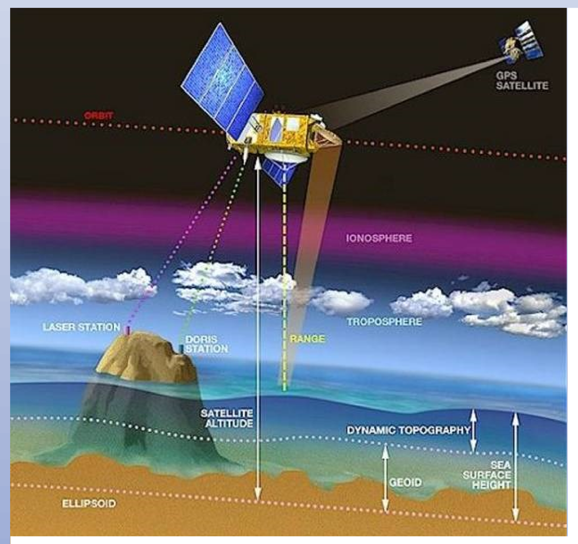

**Fig. 3**: Satellite altimetry range measurement of sea level (credit; CLS, AVISO)

### Satellite Altimetry

- Nadir pointing active microwave sensor
- Beam travel time and precise orbit determination allow distance measurement above the ellipsoid.
- Long time series available e.g., Copernicus Climate Service C3S sea level grids since 1993.
- For the time of available satellite gravity data SL is rising with $\Delta SL_{total} = 3.54 \pm 0.4$ mmyr$^{-1}$. *[1]*

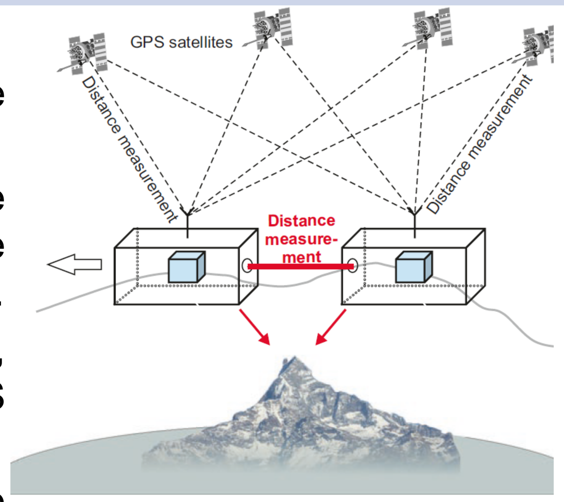


**Fig. 4**: Satellite Gravimetry principle using Satellite-Satellite-Tracking measurements. (from Angermann et al. 2022)

### Satellite Gravimetry

- Gravity is measured by precise measurements of changes in distance between twin satellites.
- Monthly solutions are available from GRAC(-FO) since 2002.
- Observation of mass changes improve our understanding climate related processes in Earth's Cryo- and Hydrosphere, as well as the mass component of sea-level rise $\Delta SL_{mass}$ : $1.83 \pm 0.21$mmyr$^{-1}$*[1]*.

## 3. Climate model projections to evaluate improvements of future satellite gravity missions

- Climate model data from CMIP6 ensemble mean projection with yearly resolution.
- Included mass changes from offline models are ice sheets and glacier signals.
- Challenging difference in magnitudes over land compared to sea:
  - Over the continents, trends are several decimeter per year
  - Over the ocean, trends are only a few millimeter per year.
- Model data from 2016 to 2100 (d/o 170) is used to answer the question:

**What improvements in accuracy of $\Delta OHC$ can be expected from the Mass change And Geosciences International Constellation (MAGIC)?**

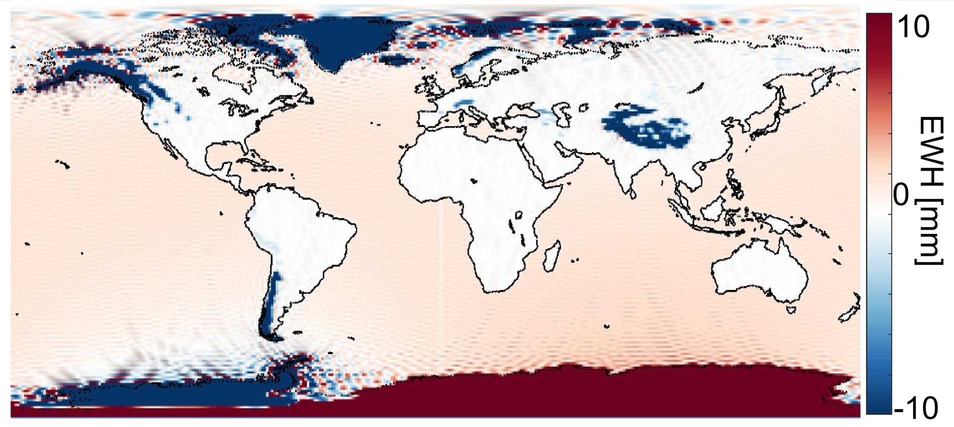


**Fig. 5**: Climate model data in mm EWH after spherical harmonic analysis to d/o 170. Example for 2016.

## 4. Closed loop simulations of future satellite gravimetry observation concept (MAGIC)

**Satellite gravity simulations *[3]***

- Gravity retrieval by least-squares adjustment based on accelerometer approach
- Satellite constellation following the current baseline scenario of MAGIC
- Time variable gravity field from simulation input superimposed by instrument noise assumptions and Ocean Tide (OT) model errors.
- Sampling along 30 day repeat orbits with 5s sampling.
  - Polar pair: 488 km, 89°
  - Inclined pair: 397 km, 70°
- Ocean Tide (OT) error is introduced through OT-model difference EOT11a - GOT4.7
- MAGIC instrument noise considers accelerometer errors ($ACC_{LoS}$), and Laser Ranging Interferometer errors for the inclined ($LRI_{MAGIC}$) and polar pair ($LRI_{GFO}$).

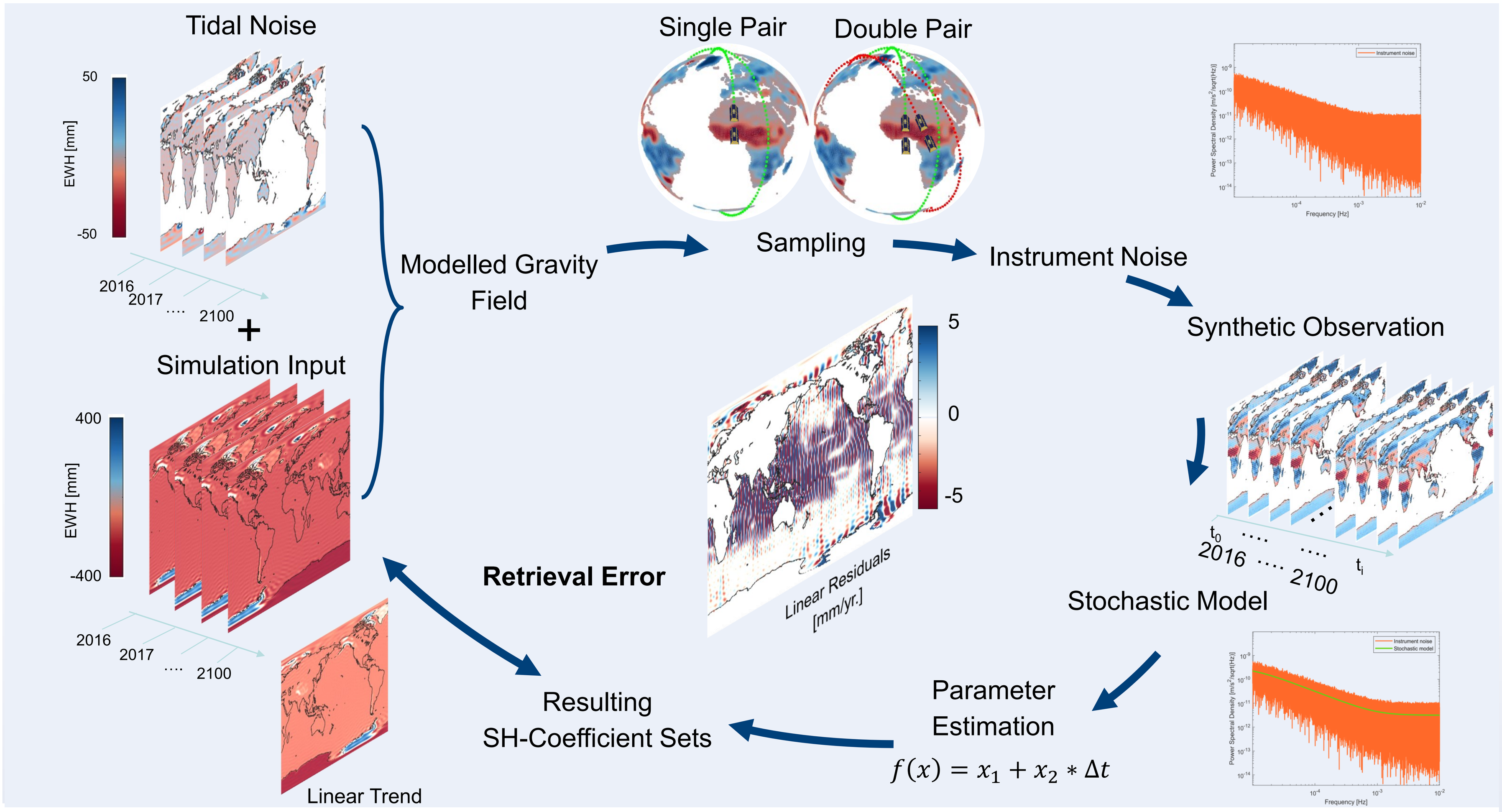


**Fig. 6**: Numerical closed loop simulation environment for single pair and double pair simulations following the MAGIC baseline scenario.

$$ACC_{LoS} = 1 \cdot 10^{-11} \sqrt{\frac{\left(\frac{0.001\mathrm{Hz}}{f}\right)^2}{\left(\left(\frac{0.00001\mathrm{Hz}}{f}\right)^2 + 1\right)} + 1 + \left(\frac{f}{0.1\mathrm{Hz}}\right)^4} \quad LRI_{MAGIC} = L \cdot \left(2 \cdot 10^{-13} \sqrt{1 + \left(\frac{0.01Hz}{f}\right)^2} \sqrt{1 + \left(\frac{0.001Hz}{f}\right)^2}\right) \quad LRI_{GFO} = \sqrt{\left(L \cdot \frac{10^{-15}}{\sqrt{f}}\right)^2 + \left(\frac{10^{-12}}{f^2}\right)^2}$$

(Eq.4) Amplitude spectral density equations of instrument errors currently assumed in the MAGIC study

## 5 . Simulation results

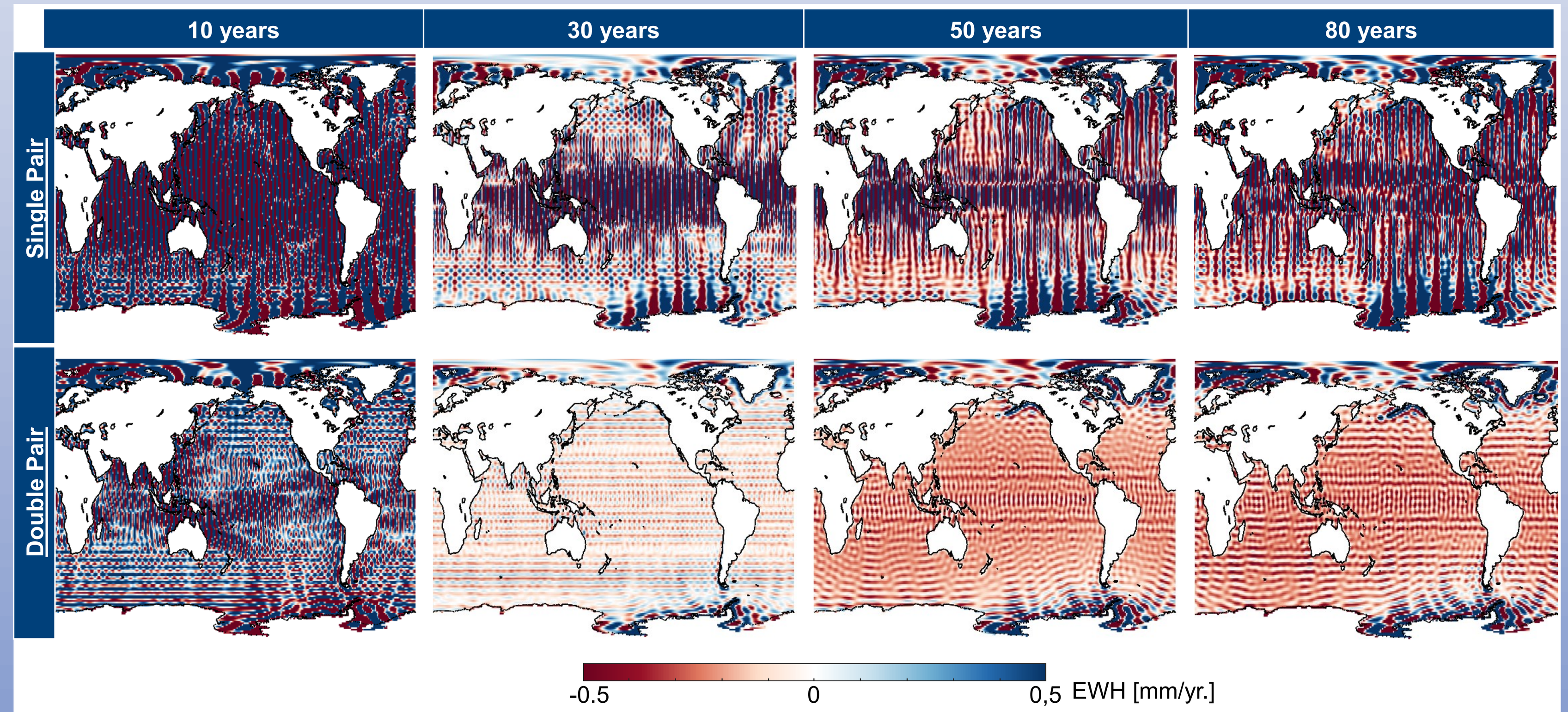


**Fig. 7**: Residuals for linear trend estimation from single (upper row) and double pair (lower row) simulations considering (from left to right) 10, 30, 50, 80 years of observations given in EWH [mmyr$^{-1}$].

| | Reference | Single Pair | Double Pair |
|---|---|---|---|
| [yrs.] | Mean $\Delta SL_{mass}$ [mm/yr.] | Ocean RMS [mm/yr.] | Ocean RMS [mm/yr.] |
| **10** | 1.16 | 7.76 | 0.86 |
| **30** | 1.85 | 0.98 | 0.13 |
| **50** | 2.44 | 0.91 | 0.22 |
| **80** | 3.76 | 0.97 | 0.26 |

**Table 1.** Mean ocean trend computed between latitudes $\lambda = \begin{cases} < 70 \\ > -70 \end{cases}$ and the corresponding root mean square error of the residuals over the ocean for single and double pair for the time intervals 10, 30, 50, and 80 years.

- Improved long-term trend (Fig. 7) with:
  - Increased observation period
  - Advanced observation system
- Aliasing errors are strongest in polar regions
- CMIP6 model data shows an acceleration of sea-levelrise over the century
- Excluding polar areas, the ocean RMS reduces even further to 1 mmyr$^{-1}$ for the single pair and 0.2 mmyr$^{-1}$ for the double pair (Table 1).
- After a couple of years OT-aliasing is no more reduced by the increased number of observations, due to the fixed orbit repeat pattern.
- The residuals show a minimum, after 30 years.
- The increase in residuals after 30 years is correlated with the accelerated ice loss increasing the Gibbs effect.

## 6. Outlook & Conclusions

- ➢ The simulation environment allows realistic estimation of satellite gravity observations for GRACE-FO and MAGIC constellation for Spherical Harmonic (SH) degree 80. In future work it is planned to increase the maximum degree and order to 160.
- ➢ Large difference in the input signal magnitude between continents and ocean causes Gibbs phenomena in the SH representation, especially in regions of intense and localized signals.
- ➢ Post-processing of simulation results is still to be done. As well as the computation of the thermosteric sea-level change $\Delta SL_{thermo}$ to evaluate the gain in accuracy that is to be expect from MAGIC for the assessment of EEI.
- ➢ MAGIC already shows a clear improvement in RMS estimating $\Delta SL_{mass}$ especially in the areas covered by the inclined pair between the latitudes -70 and 70.

**Acknowledgements:** We acknowledge the provision of supercomputing resources by the Leibniz Supercomputing Centre (LRZ; Address: Boltzmannstraße 1, 85748 Garching bei München, Germany)

**References:** [1] Marti, Florence; Blazquez, Alejandro; Meyssignac, Benoit; Ablain, Michaël; Barnoud, Anne; Fraudeau, Robin et al. (2022): Monitoring the ocean heat content change and the Earth energy imbalance from space altimetry and space gravimetry. In *Earth Syst. Sci. Data* 14 (1), pp. 229–249. DOI: 10.5194/essd-14-229-2022.
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Vienna, Austria, 23-28 April 2023

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