Chasing small amplitudes signals from the deep Earth's interior in GRACE measurements

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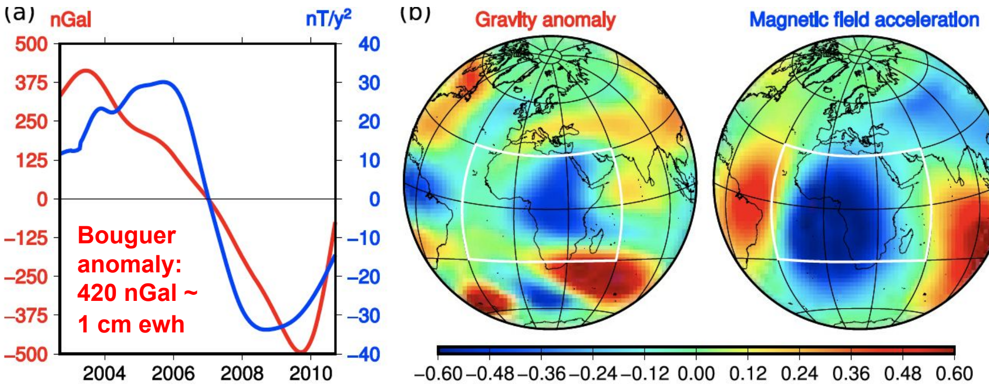
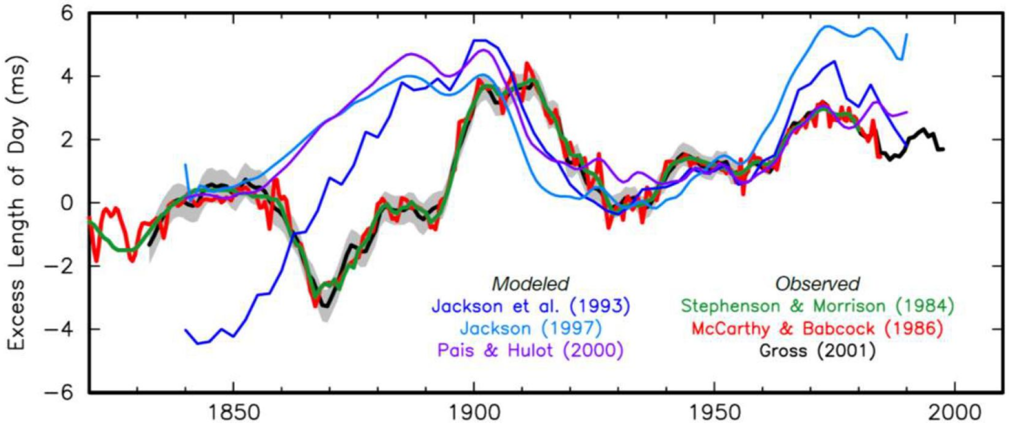
Origin of the GRACEFUL project

GRACEFUL is an ERC Synergy project dedicated to detect deep Earth's signals in satellite observations of the magnetic field, gravity field and rotation

Objectives: explore fluid motions in the **outer core** and cristallisation/dissolution processes at the **core mantle boundary**

Motivation: discovery of spatio-temporal **correlations between the magnetic field and gravity field** at interannual time-scales by Mandea et al., 2012 (PNAS) and 2015 (JGR)





Challenges for the analysis of the gravity field

Challenge:

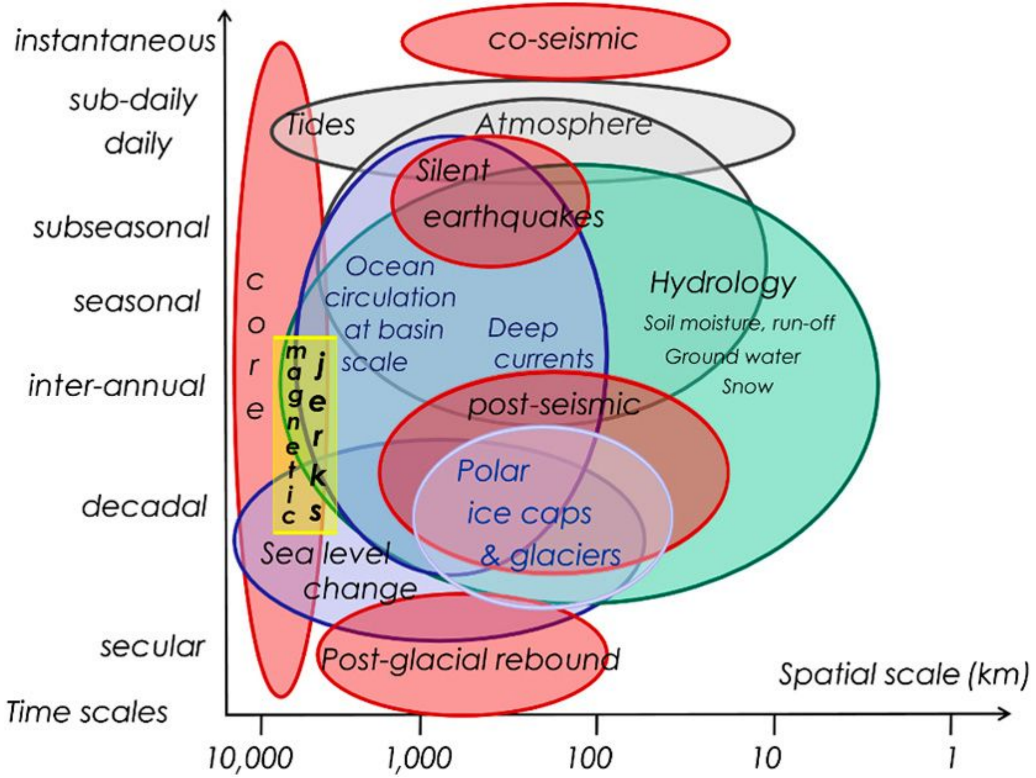
Gravity signals originating from the deep Earth interior are masked by shallower geophysical processes, including the:

- global water cycle
- glacial isostatic adjustment
- earthquakes

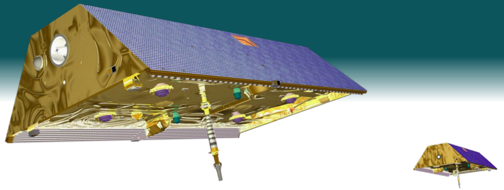
What we need to do :

- correct GRACE and GRACE-FO observations for surface effects
- estimate the uncertainties on satellite gravity data and surface corrections.

Processes causing changes at various temporal and spatial scales in the Earth's gravity field (Mandea et al., 2012)



Satellite gravity data processing



❖ Collection of time-lapse satellite gravity data from GRACE and GRACE Follow-On

- Average of monthly **surface mass anomalies** from 3 mascon (JPL, CSR, GSFC) and 6 spherical harmonic (JPL, CSR, GFZ, ITSG, COST-G, CNES-GRGS) solutions from April 2002 to December 2021

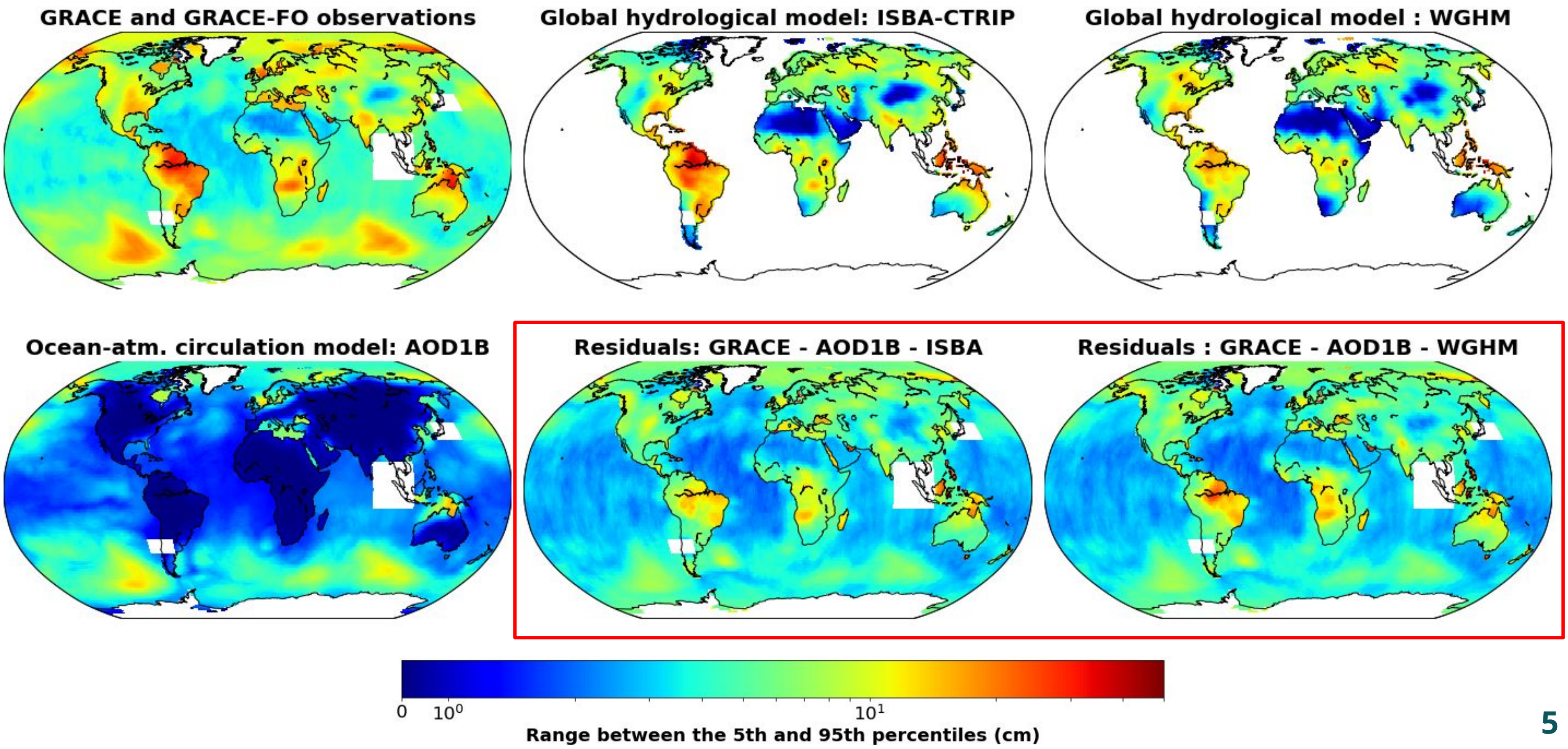
❖ Application of geophysical corrections

- **Glacial isostatic adjustment** : ICE6G-D
- **Ocean-Atmosphere circulation** **:** AOD1B Release 6 (GAD)
- **Hydrology** : ISBA-CTRIP and WGHM
- Additional correction for **lakes** based on satellite altimetry from hydroweb (Blazquez et al., in prep)

❖ Processing of residual surface mass anomalies

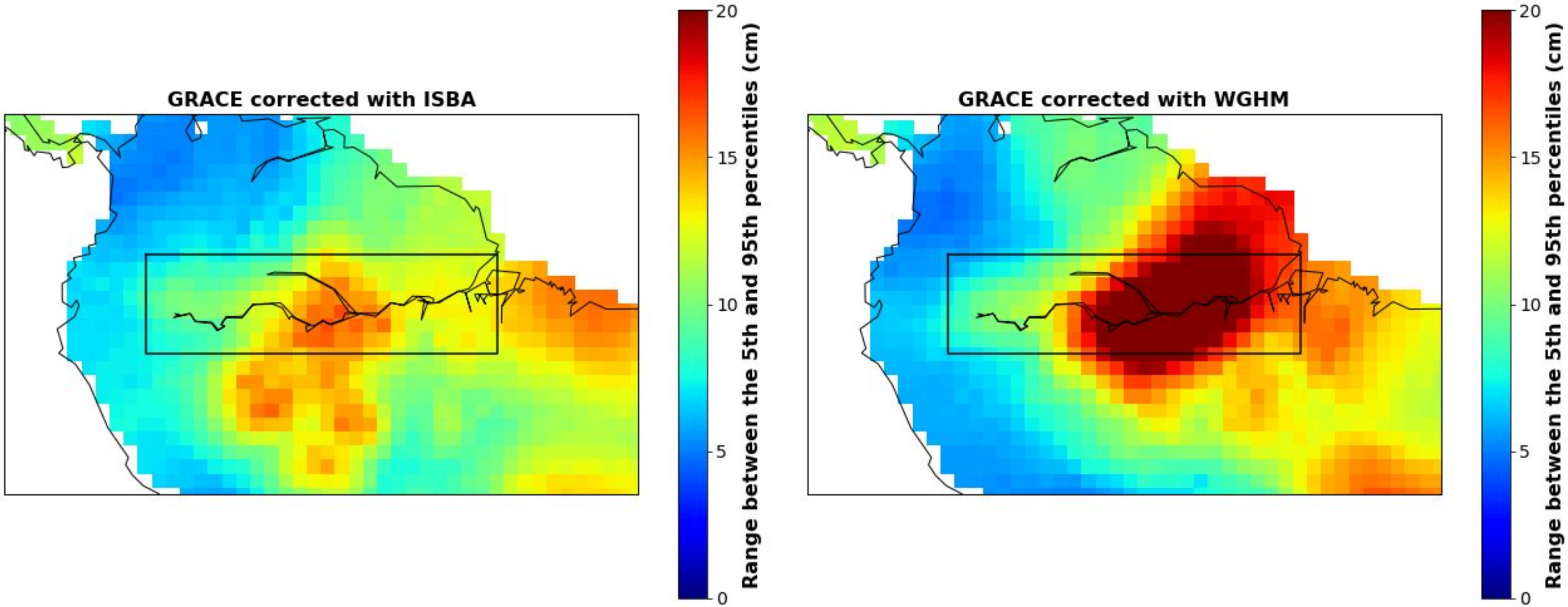
- Application of geographical masks over **ice-sheets** and regions impacted by large **earthquakes**
- **Focus on interannual time scales**: removal of linear trend, annual-sinusoid and semi-annual sinusoid
- Application of a **spatial filter** (radius: 250 km) based on diffusion (Goux et al., submitted to GJI)

Amplitude of interannual gravity signals



The case of the central Amazon corridor

Amplitude of detrended and deseasoned mean residual mass anomalies



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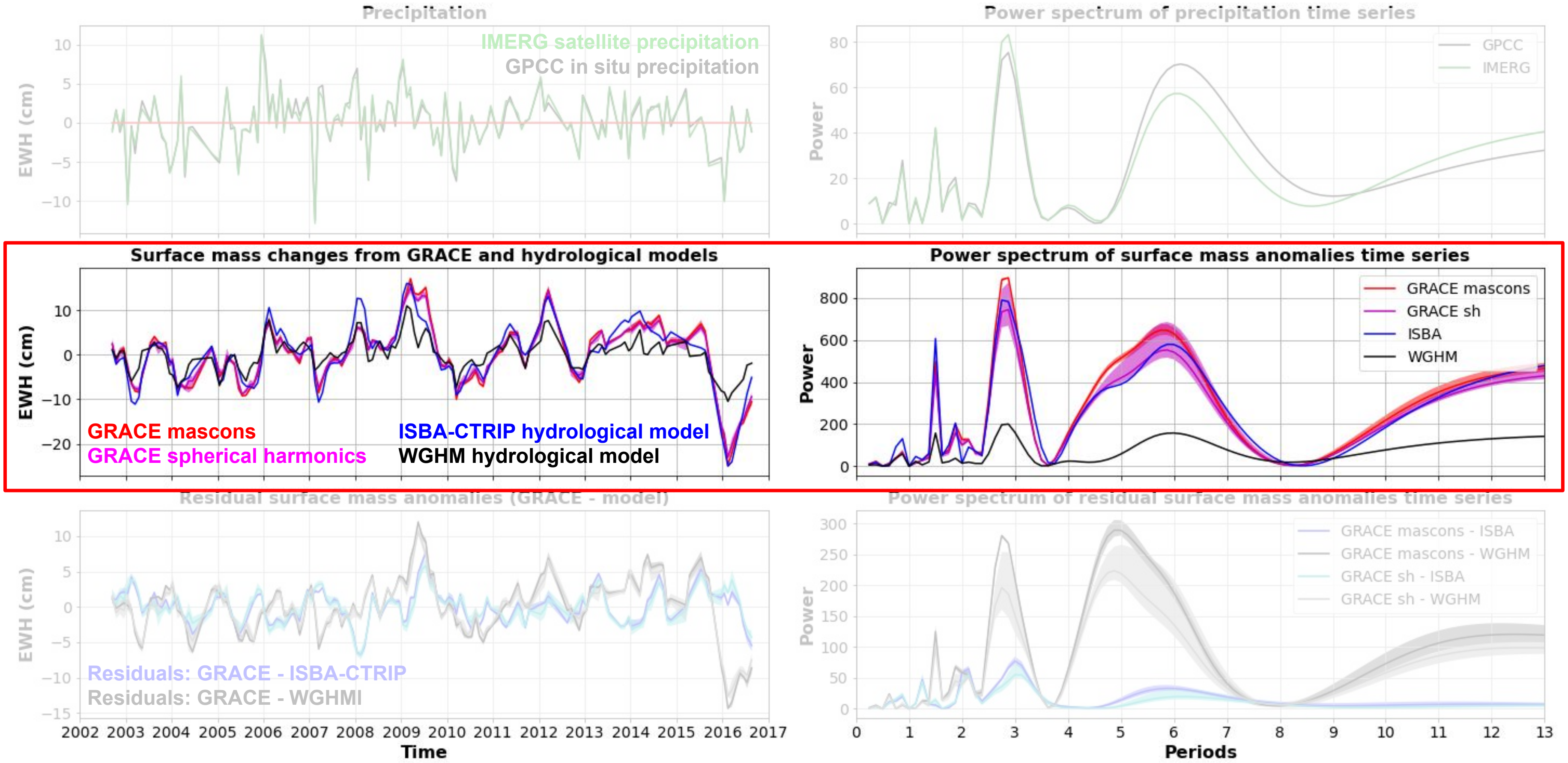

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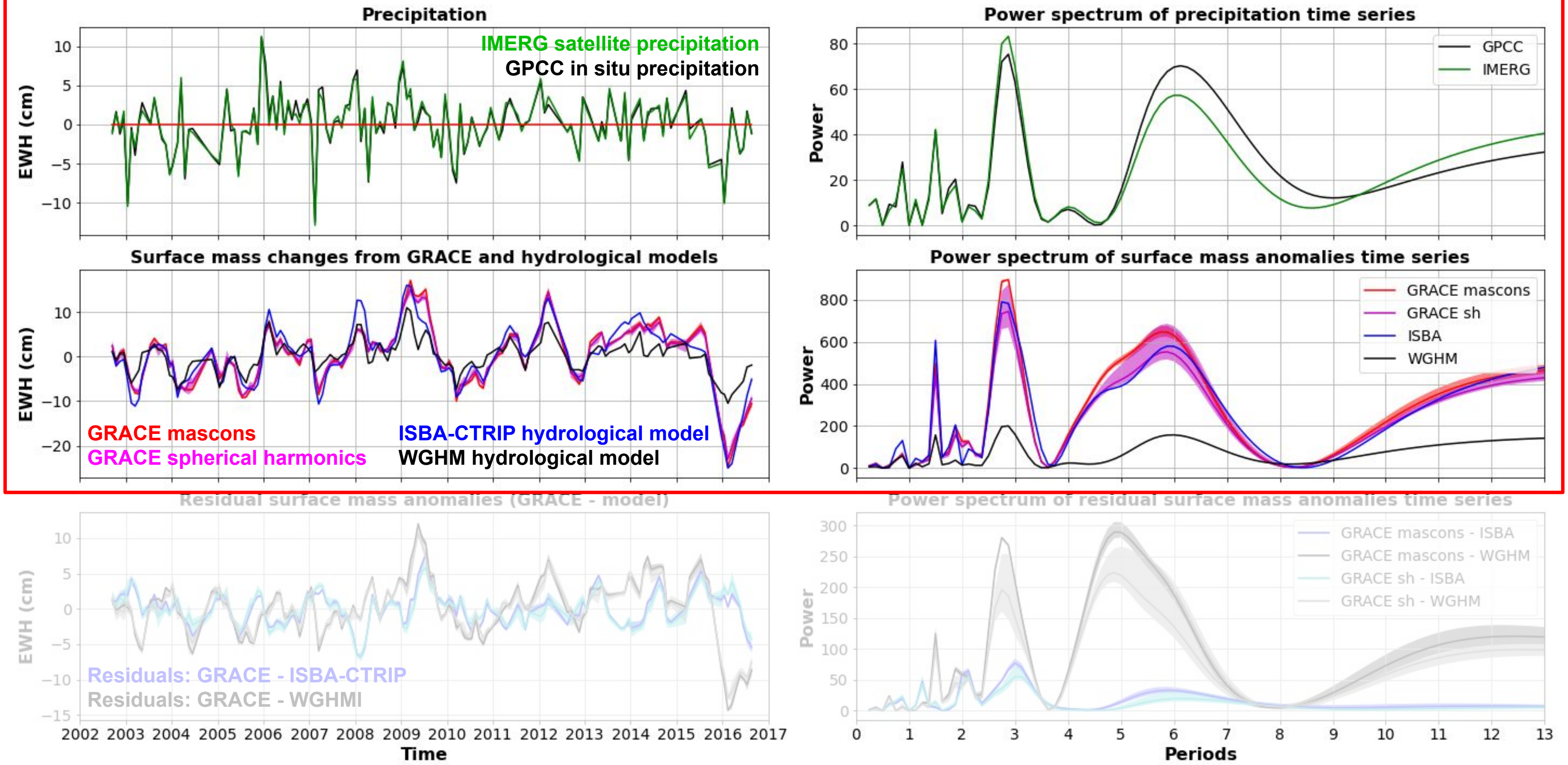

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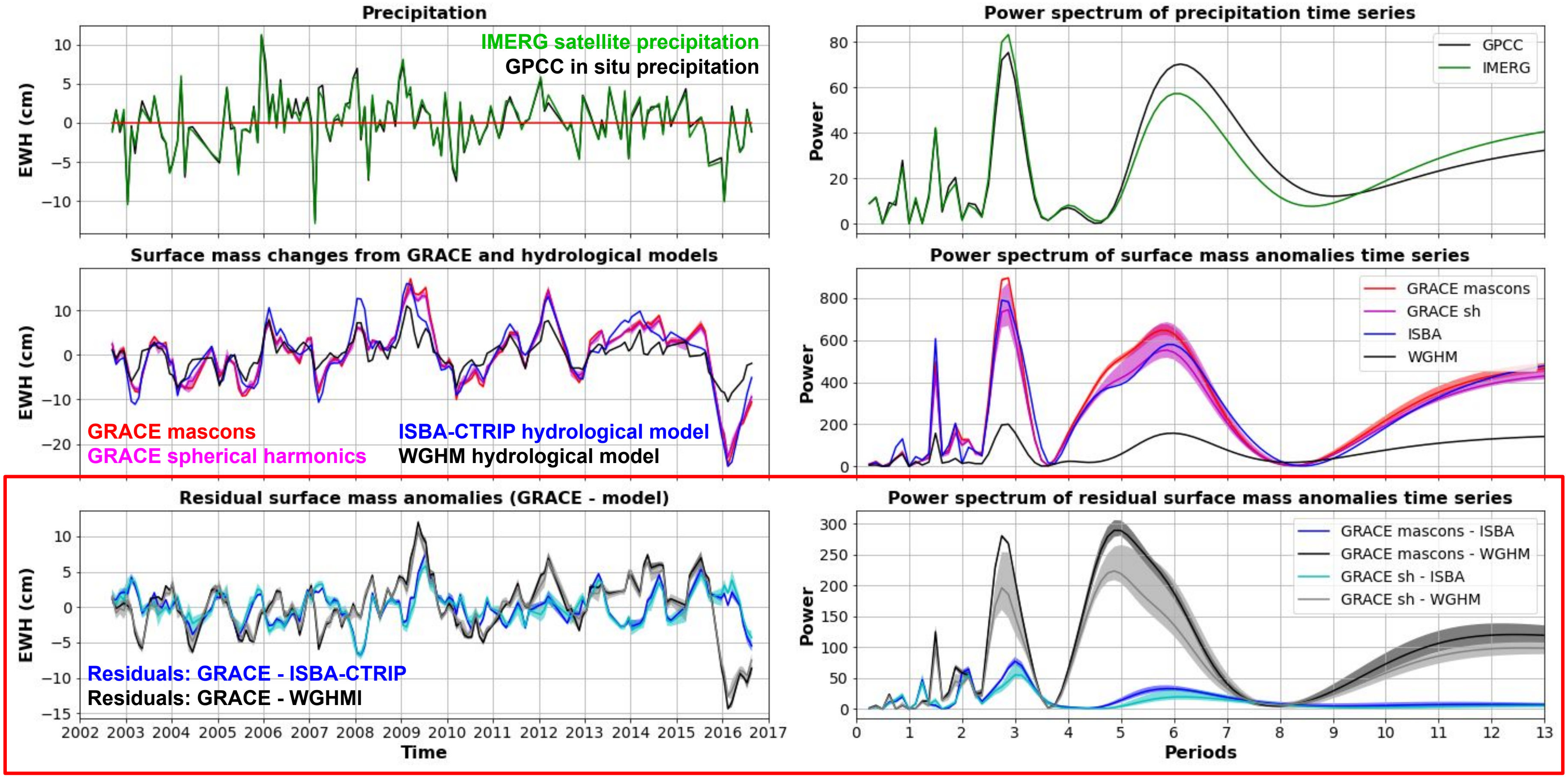

The case of the Zambezi river basin

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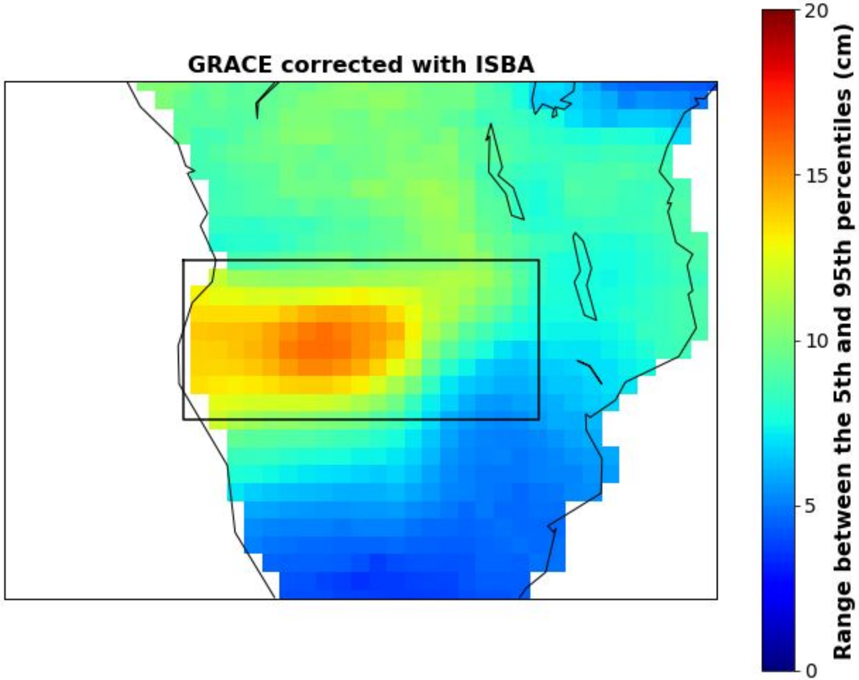
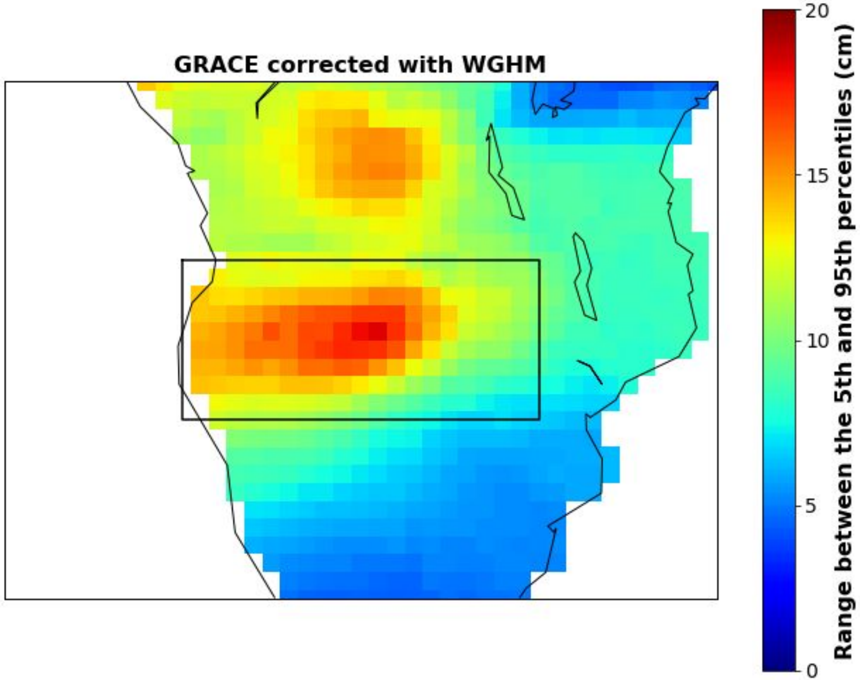
Amplitude of detrended and deseasoned mean residual mass anomalies





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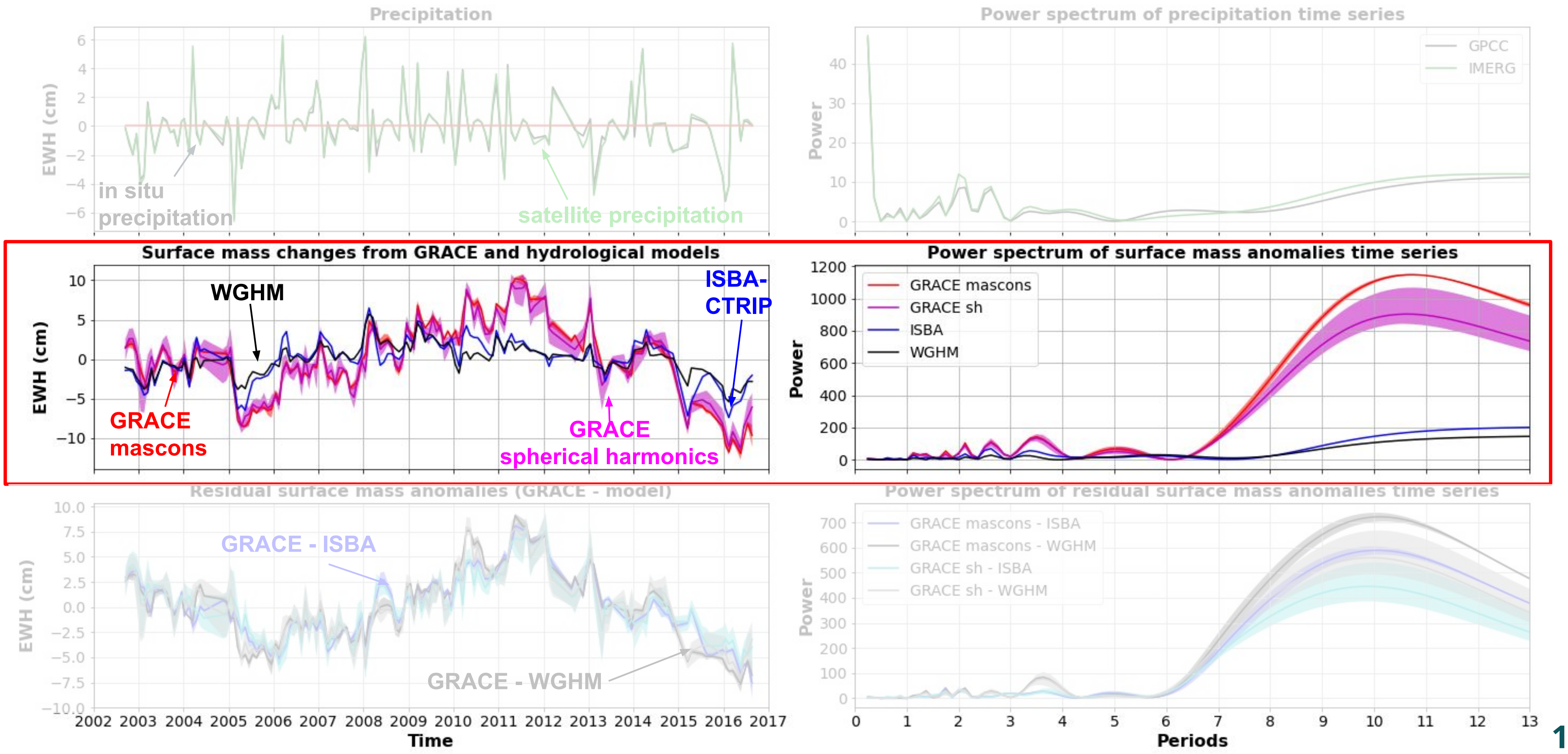

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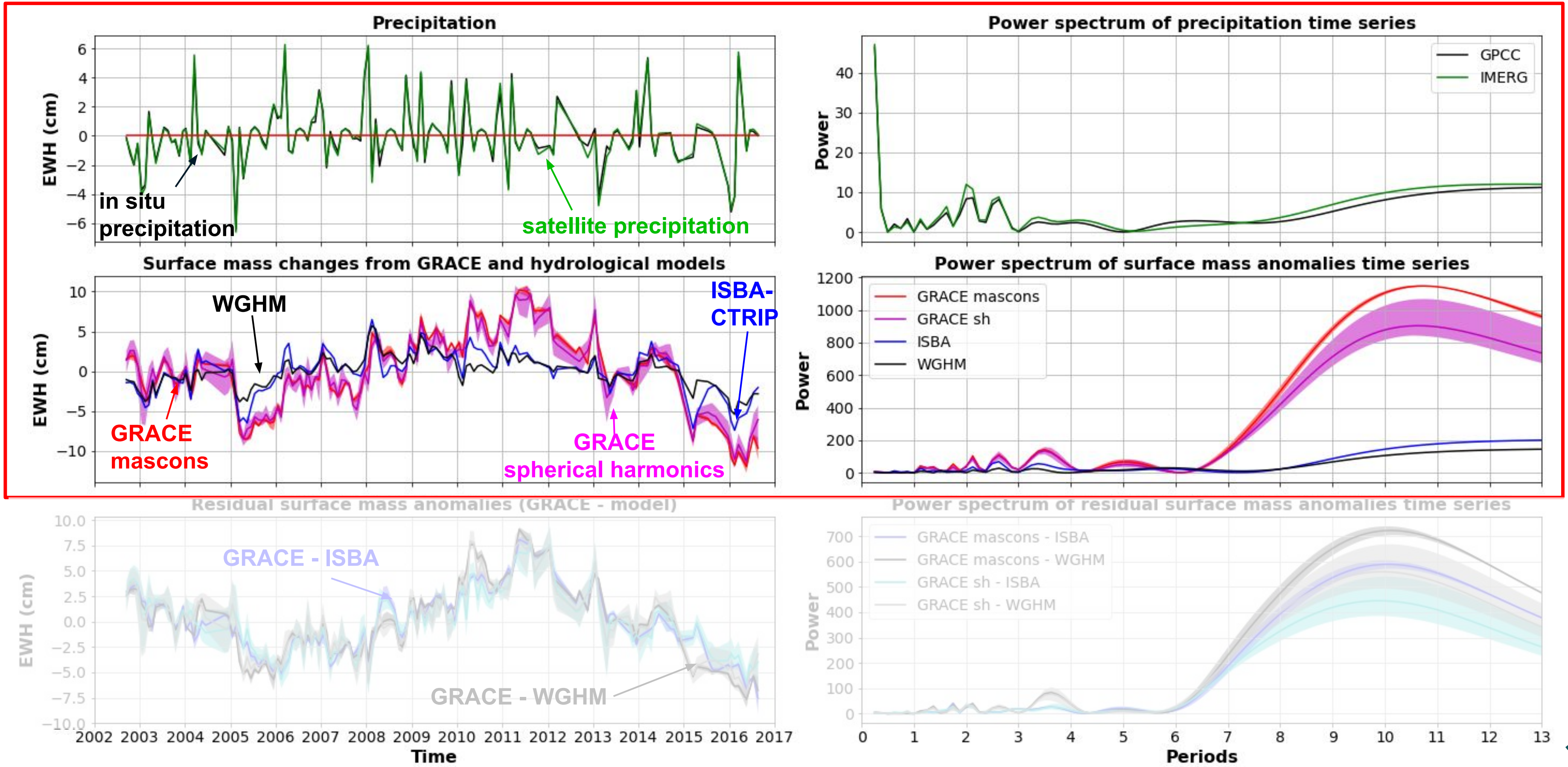

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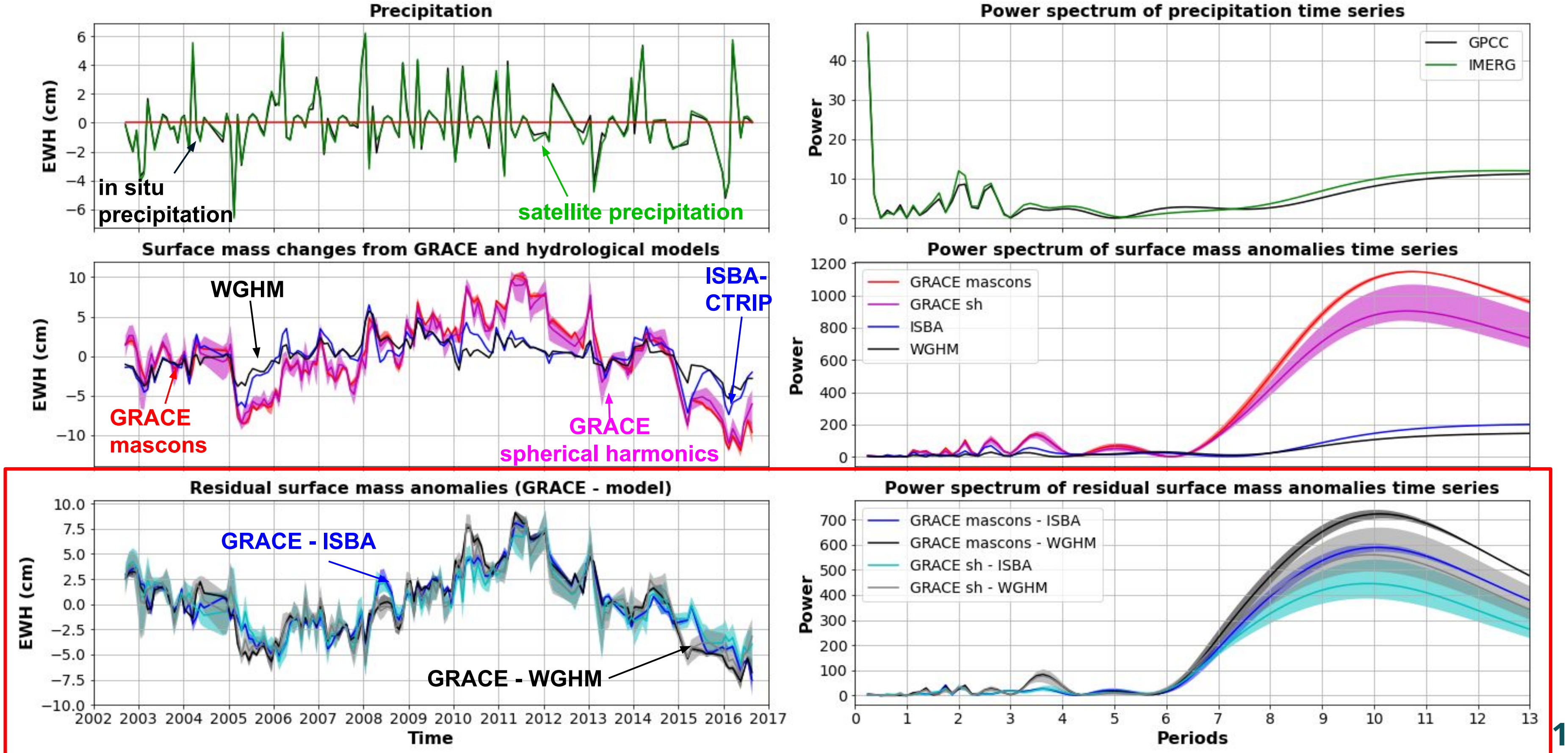

The case of the Congo basin

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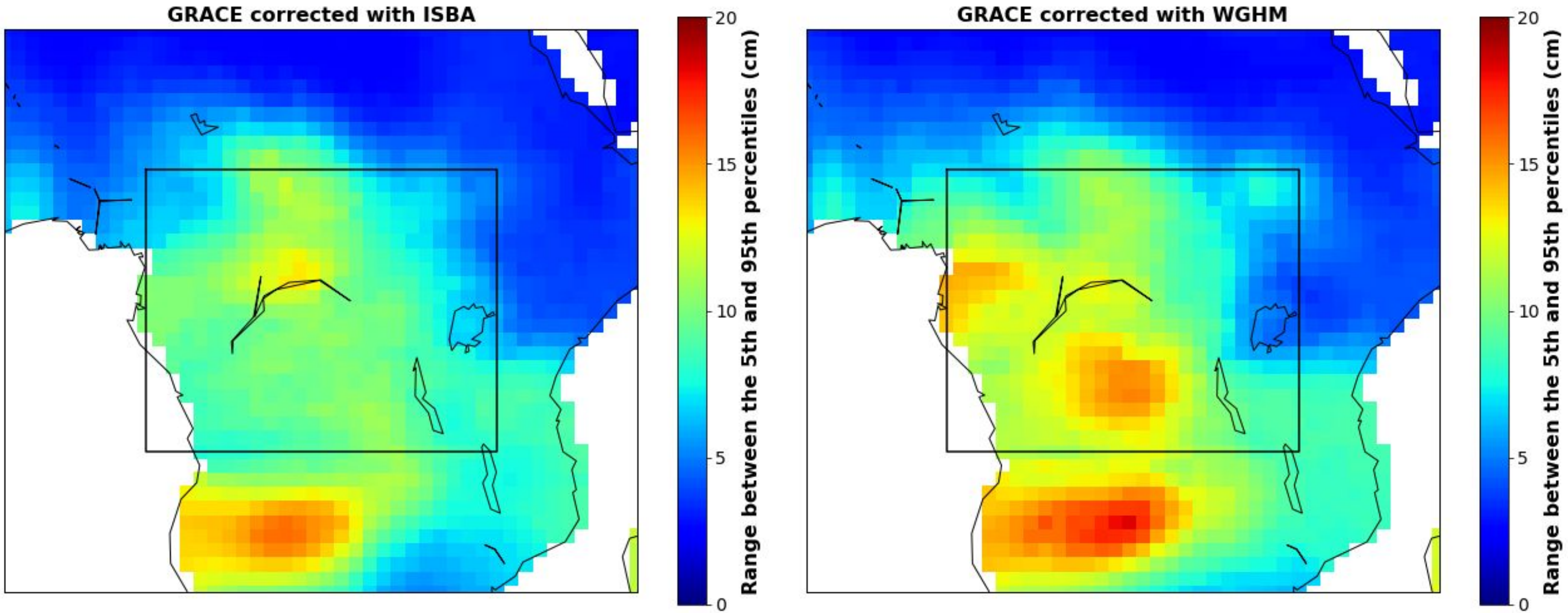

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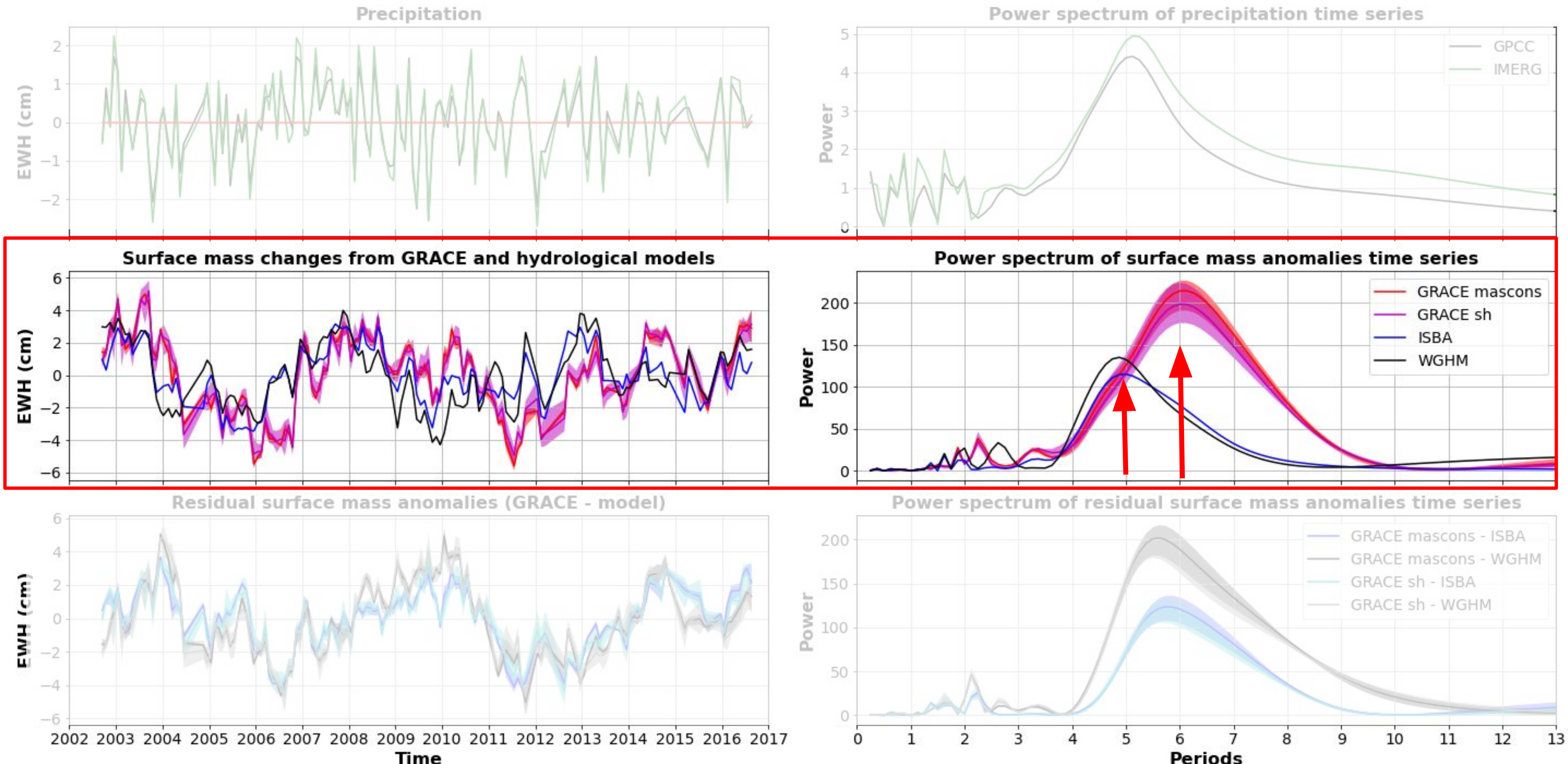

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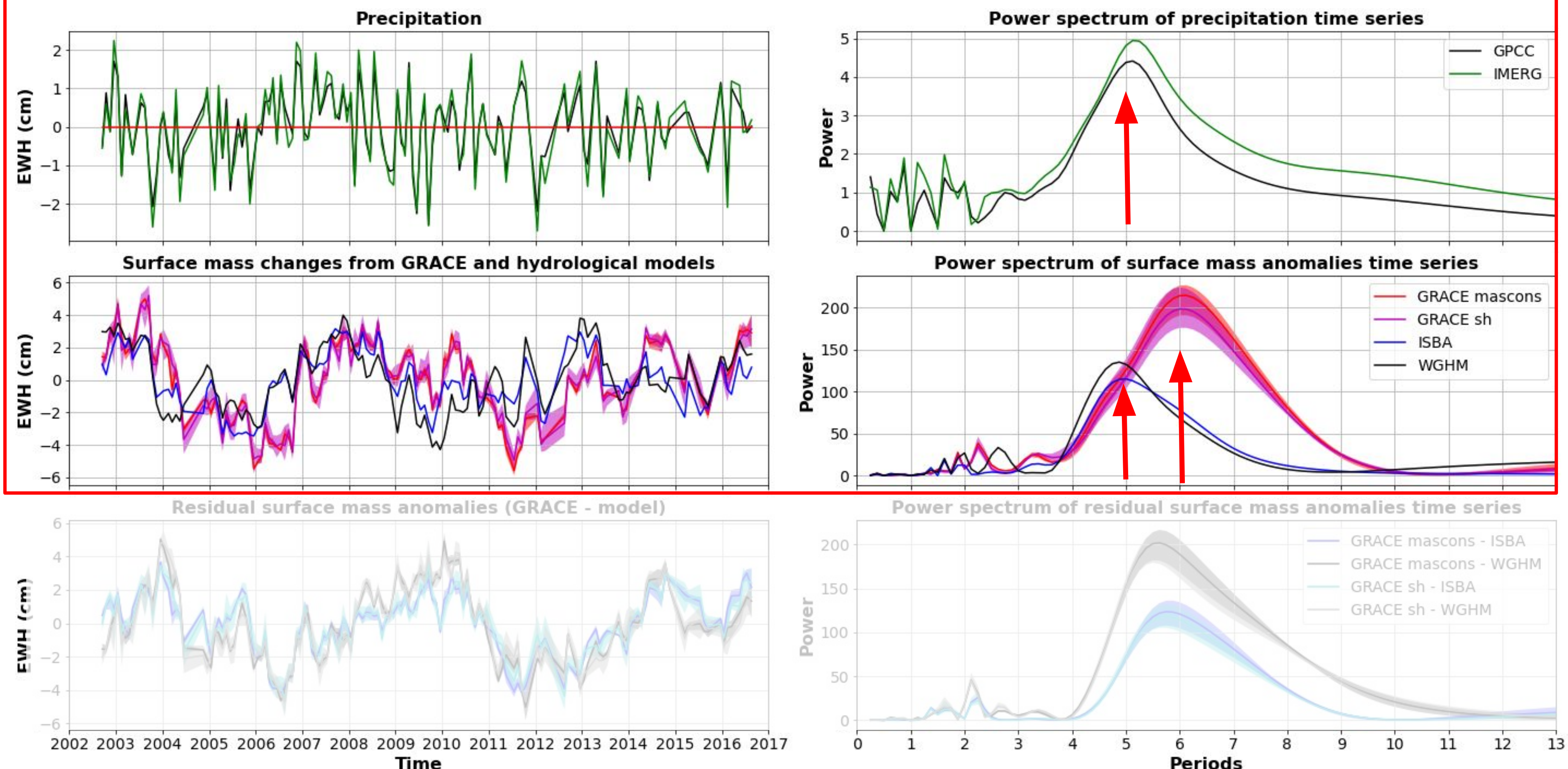

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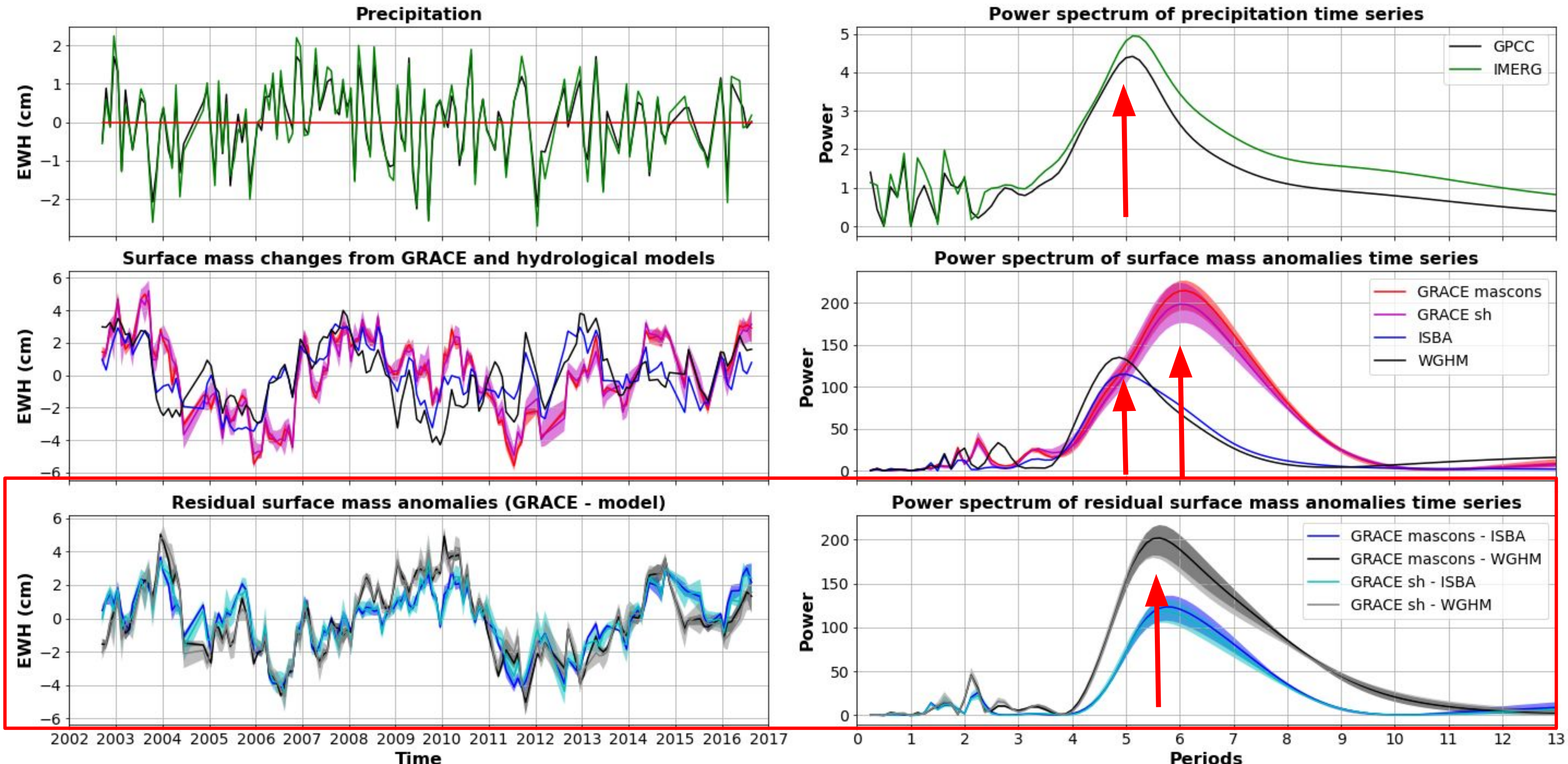
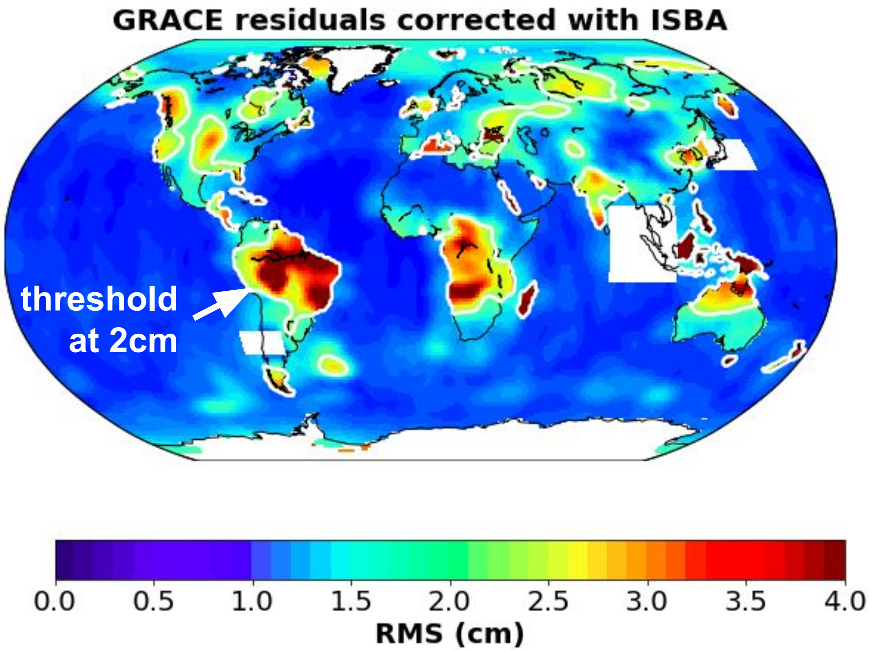
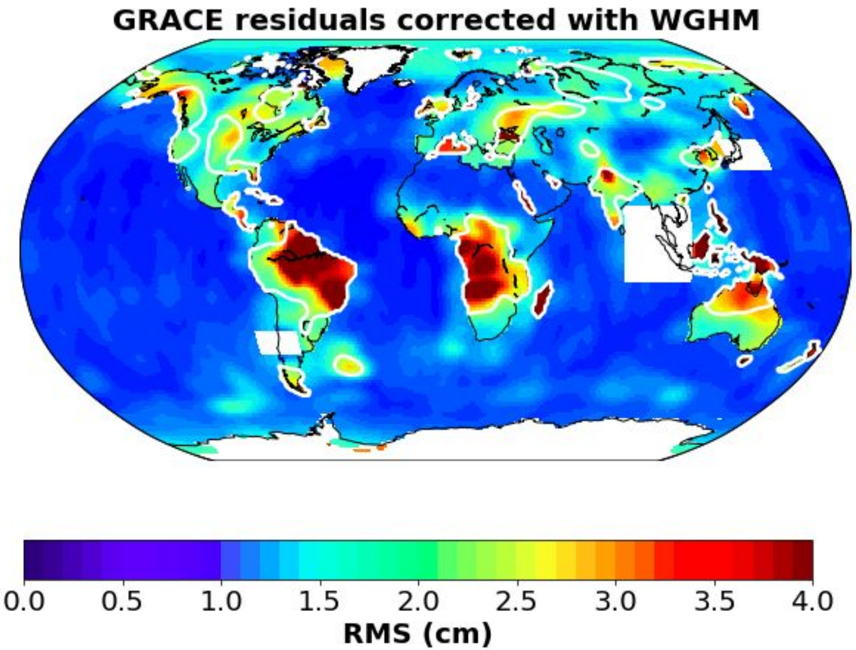
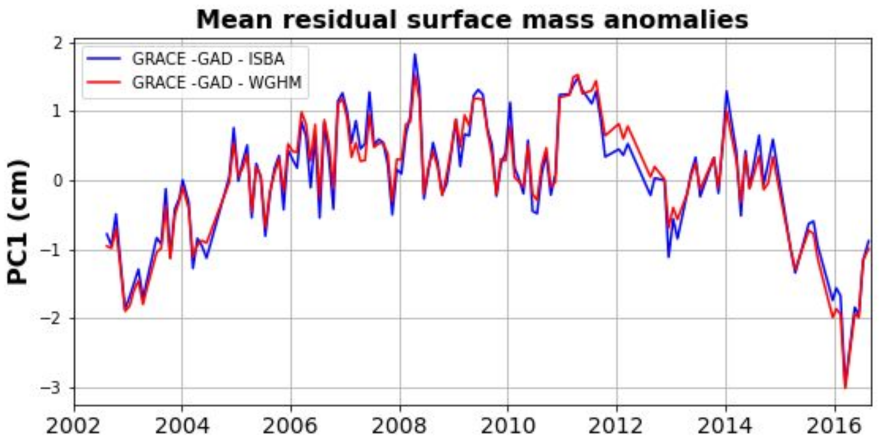


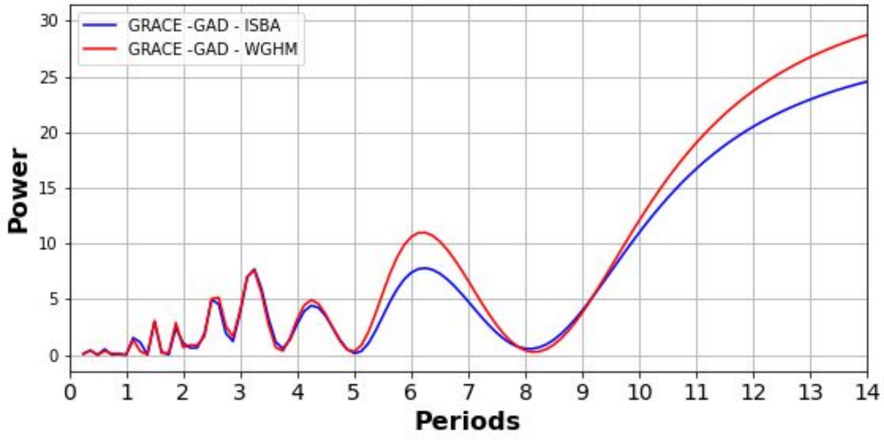
What do residual mass variations look like in "quiet" regions of the world?

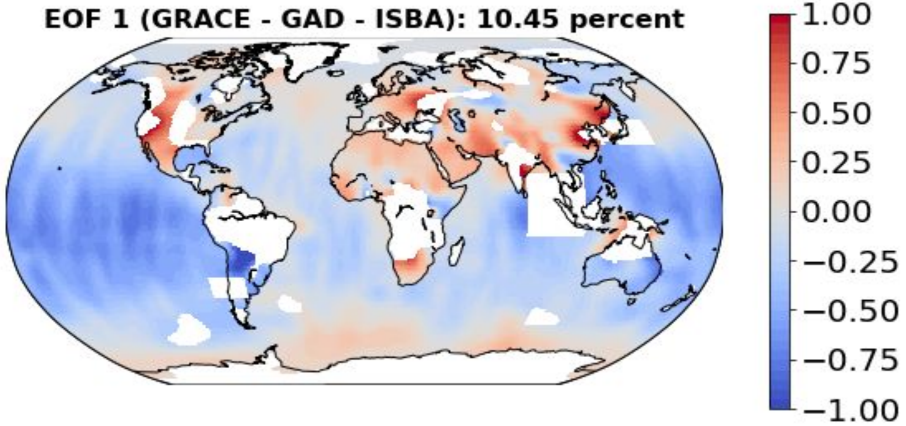


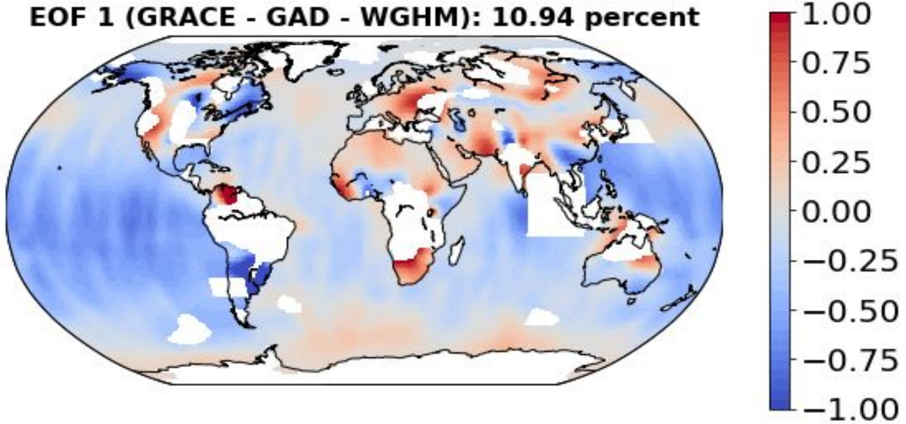


Dominant signal in residual surface mass anomalies

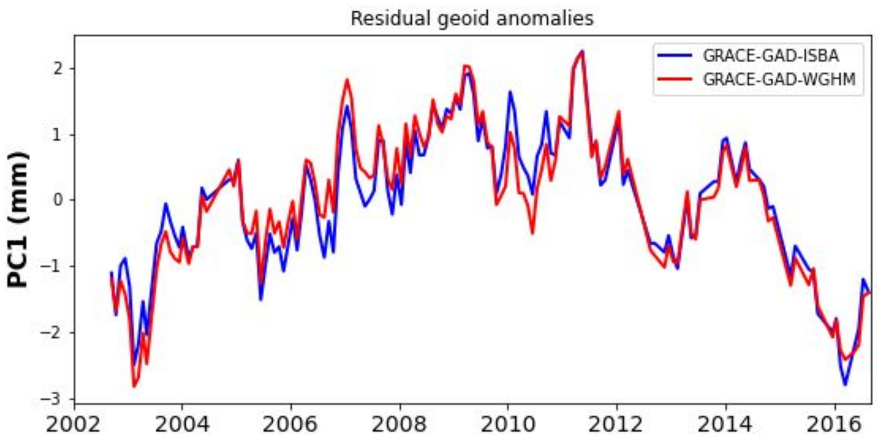


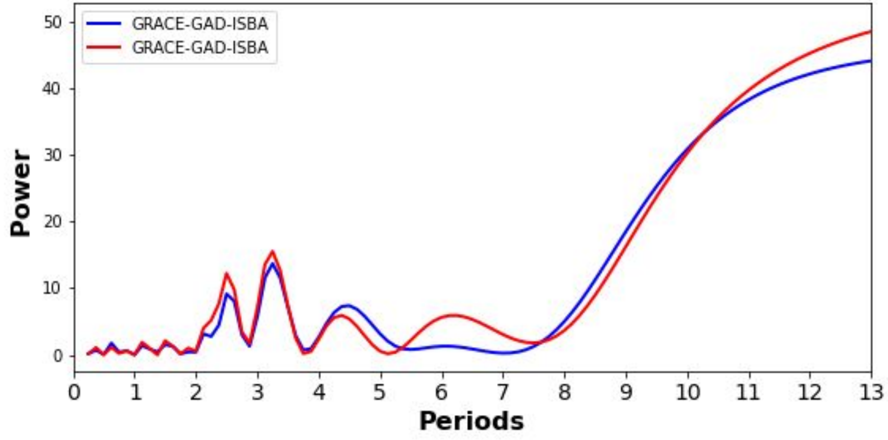


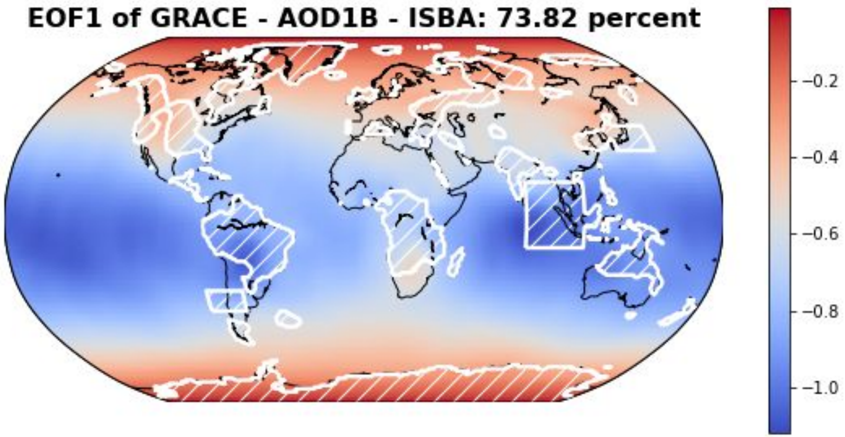


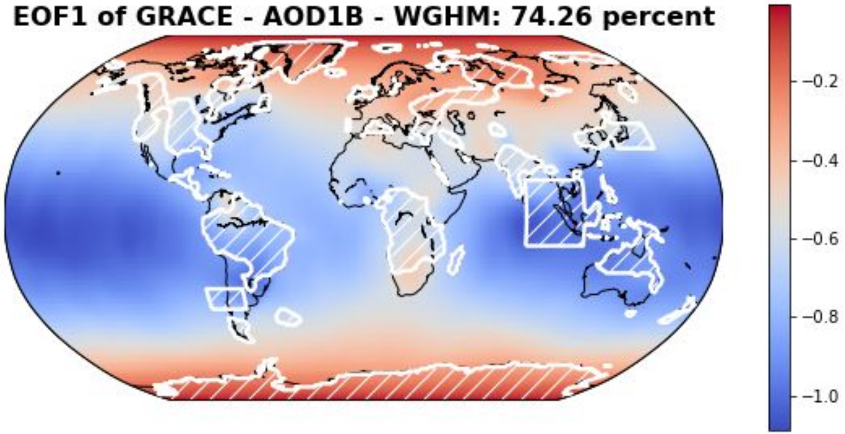


Dominant signal in residual **geoid** anomalies



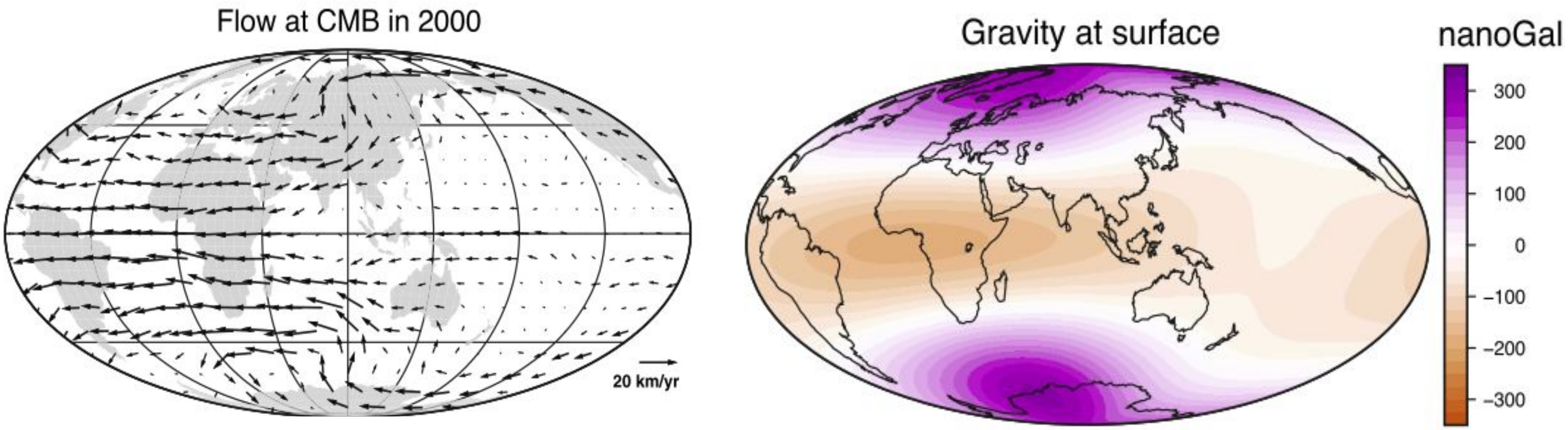






Flow at the Core Mantle Boundary

Bouguer anomaly:
1cm EWH → 420 nGal



Gravity change at the surface (right) associated with the flow at the CMB in 2000 (left).

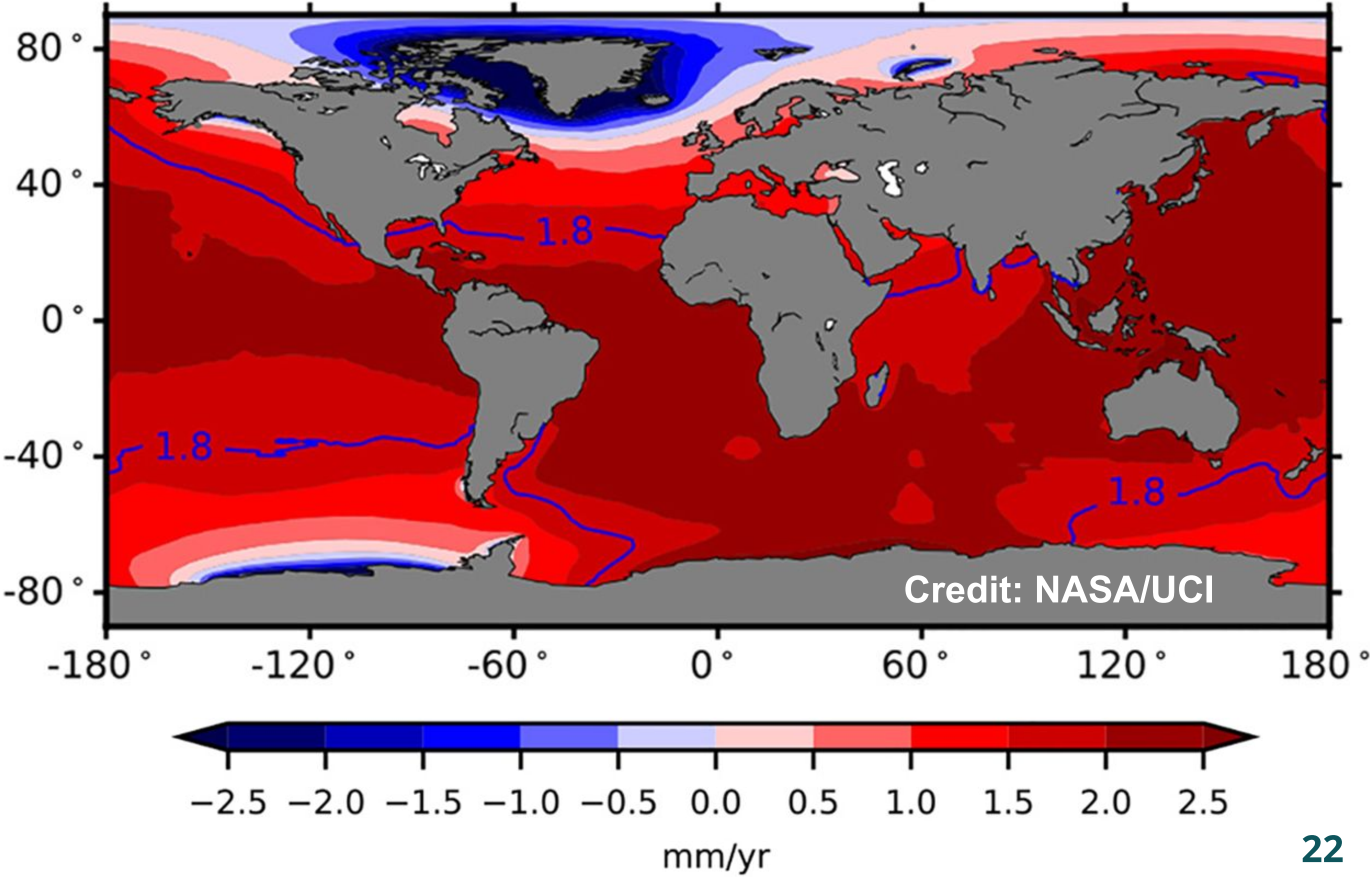
The flow model is the ensemble average of the flow models in Barrois et al. (2017) truncated at degree 11

From Dumberry & Mandea (2021) Surveys in Geophysics [10.1007/s10712-021-09656-2](https://doi.org/10.1007/s10712-021-09656-2)

Sea level fingerprints associated with the loss of ice from glaciers and ice sheets and from changes in terrestrial water storage.

Hsu & Velicogna, 2017 (GRL)

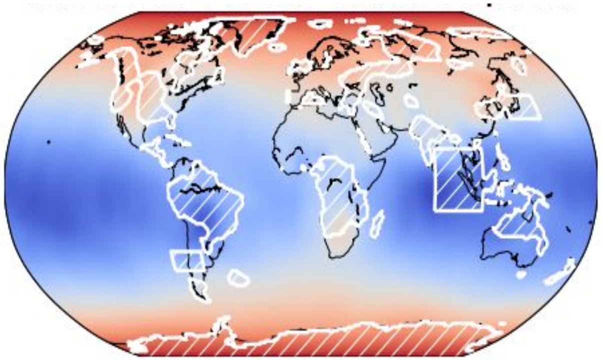
https://doi.org/10.1002/2017GL074070



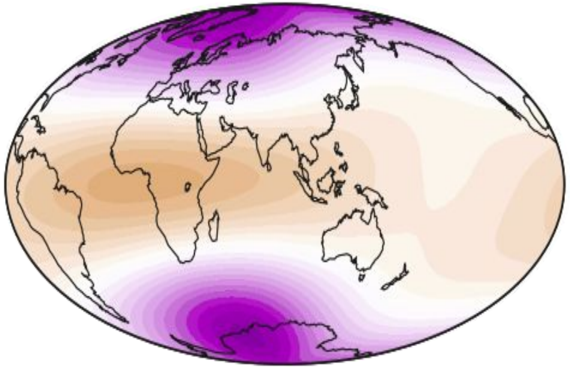
Conclusions

- The GRACE and GRACE-FO have been corrected for surface effects. **The hydrological models ISBA-CTRIP and WGHM struggle to predict pluri-annual to decadal variations in the water storage**.
- **In “quiet” regions, residual mass anomalies display characteristics that would be expected from the deep Earth’s interior**: amplitudes < 2 cm, very large scale features (1 000 to 10 000 km), remarkable continuity between the oceans and the continents, typical time-scales from a few years to 1.5 decade.
- **The origin of such signals remains unknown**: large-scale climate or deep Earth’s interior?

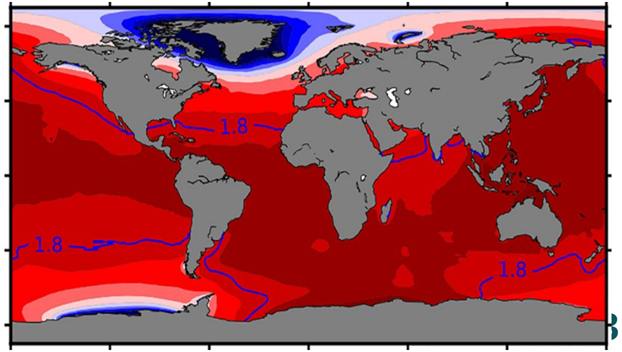
Dominant spatial feature in residual geoid anomalies from GRACE



Surface gravity change associated with flow at the CMB



Sea level fingerprint associated with ice-melting and TWS changes



Future work

- **Improve the estimation of residual mass anomalies from satellite gravity data**
  - Inclusion of additional models (hydrology) and corrections (geocenter, C20)
  - Search for optimal corrections, models and parameters
- **Improve the estimation of the uncertainties**
  - Estimation of the dispersion of the ensemble of residual mass anomalies
  - Search for advanced signal characterization method (aka: go beyond eofs!)
- **Identify the mechanisms responsible for the residual gravity field variations**
  - Comparison with satellite observations of the magnetic field and length of day
  - Investigation of deep Earth's dynamic processes by comparison with numerical models
  - Investigation of "slow" climate forcings: sea level fingerprints, wind patterns, climate indices...

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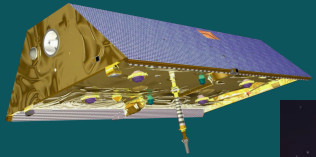

Thank you for your attention.

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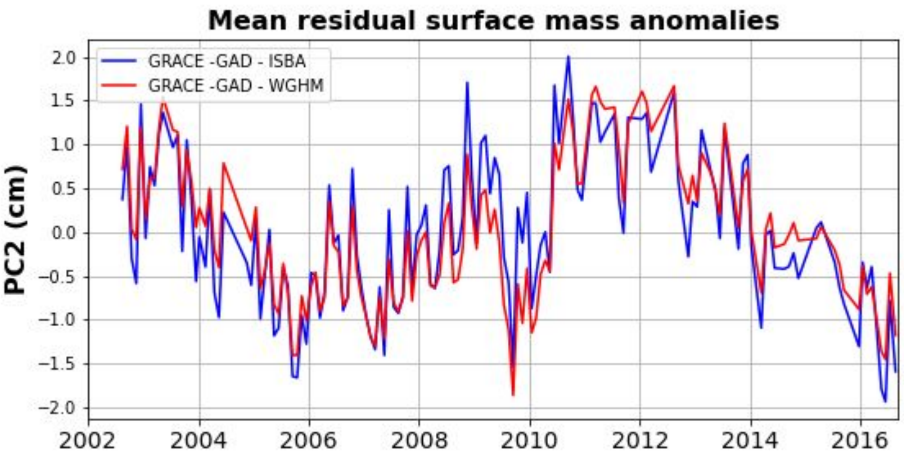
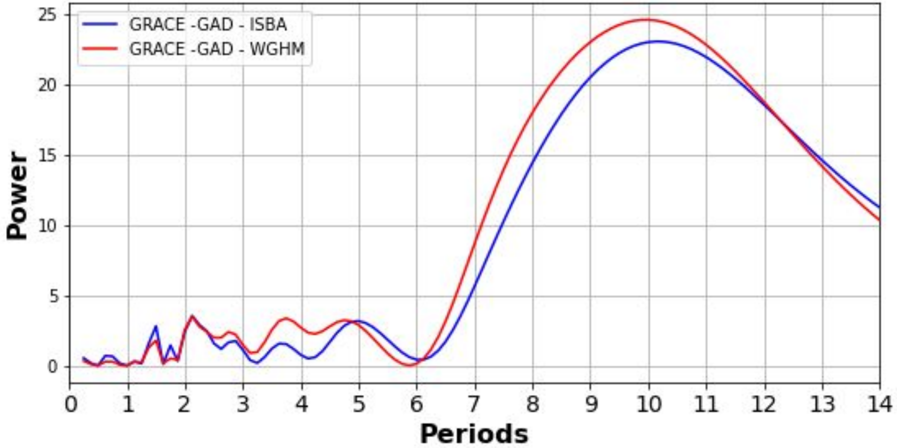
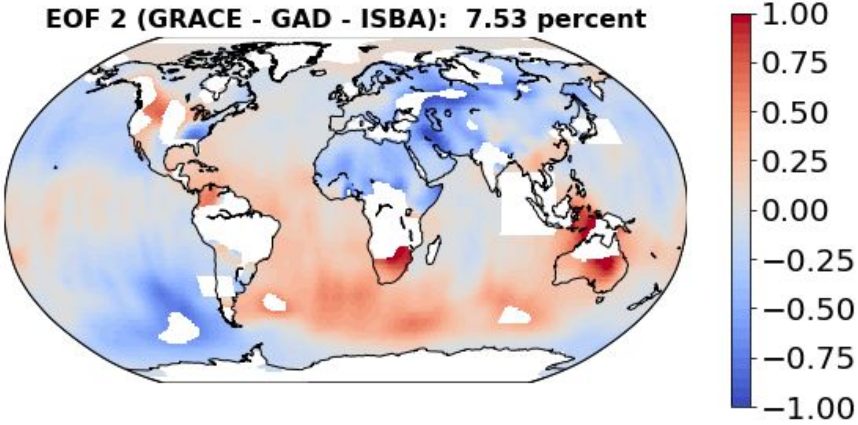
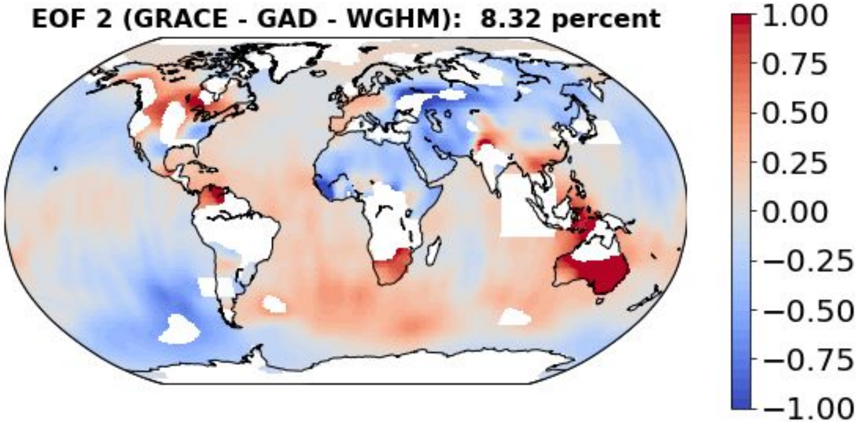
https://graceful.oma.be/

Second component of residual surface mass anomalies

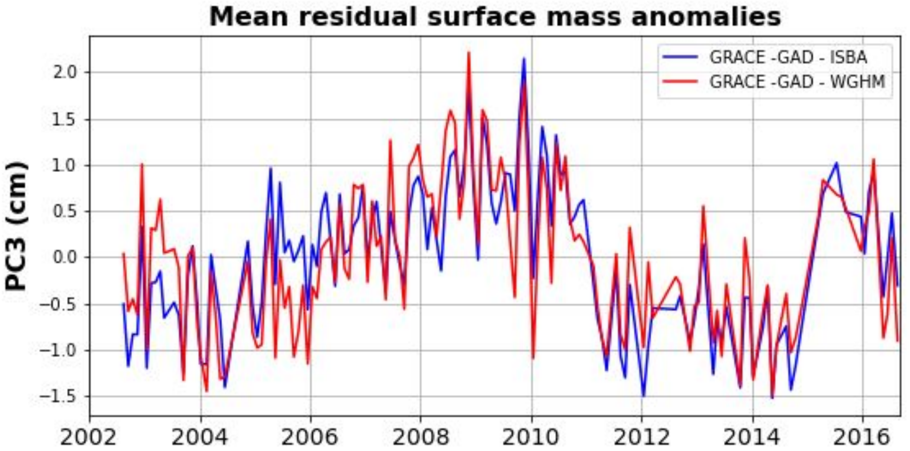


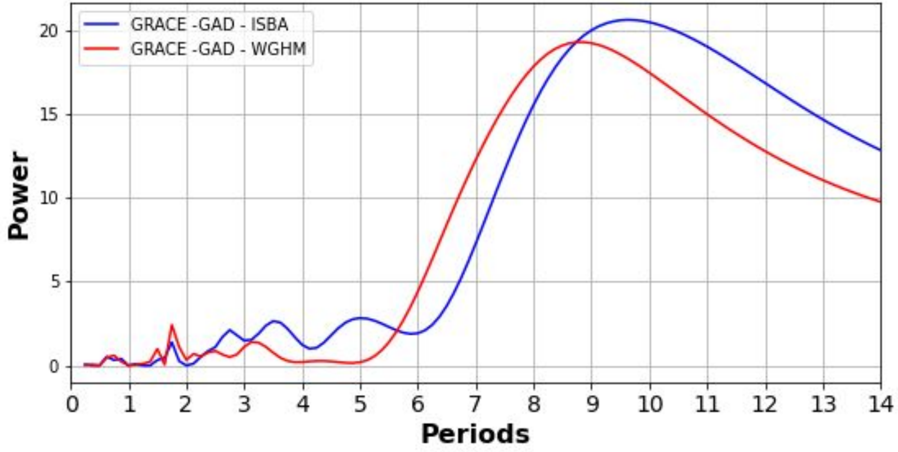


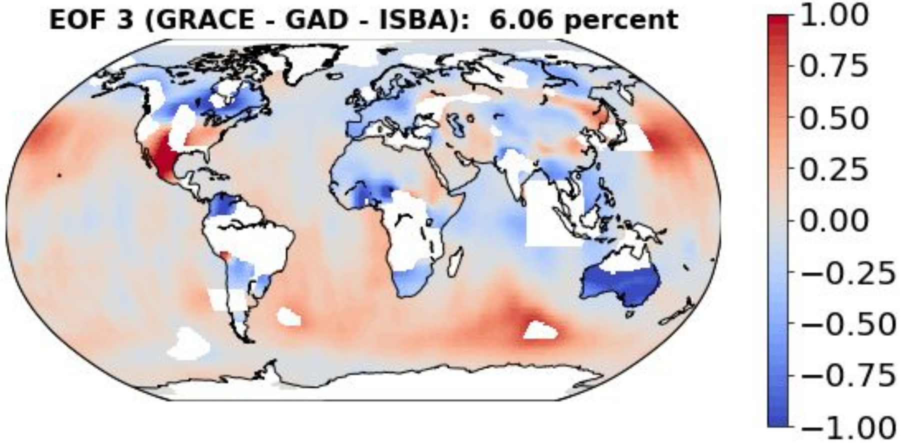


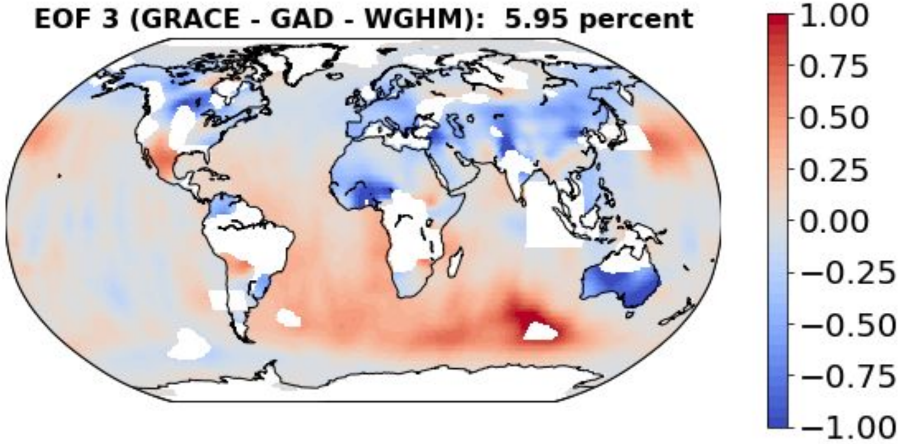


Third component of residual surface mass anomalies





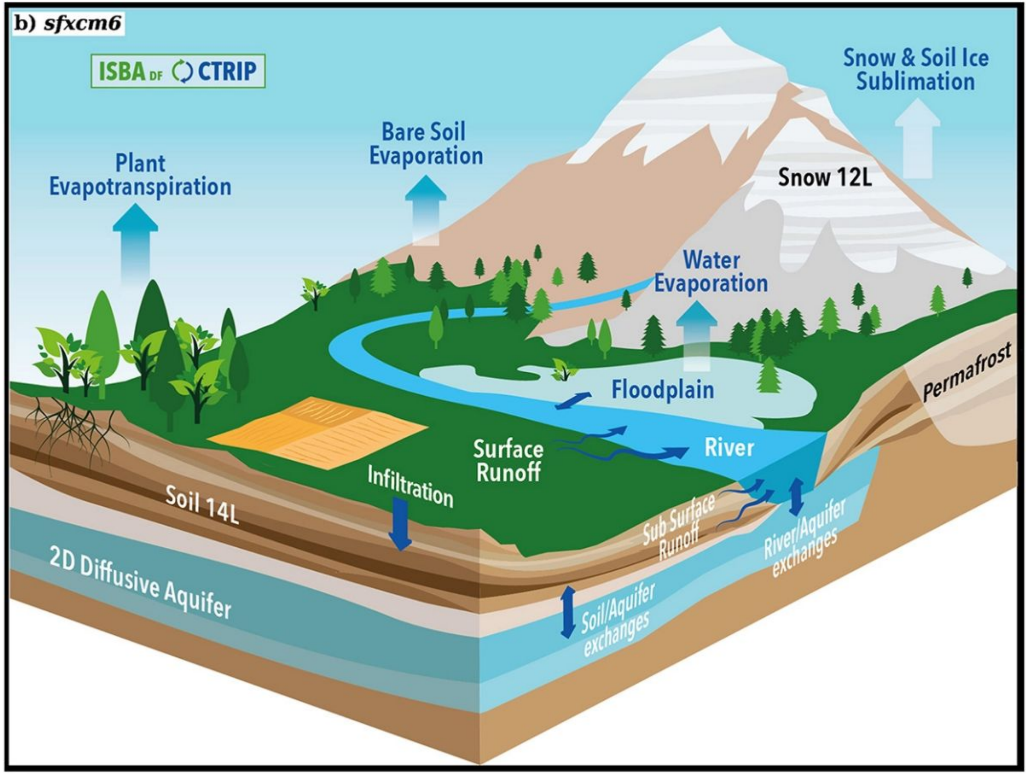




Hydrological models

ISBA-CTRIP:

- **ISBA solves the water and energy balance** in the soil, canopy, snow and surface water bodies.
- **CTRIP simulates runoff** through the global river channel network.
- **ISBA and C-TRIP are coupled through the land surface interface SURFEX**, allowing interactions with floodplains and groundwater, modelled with a 2D diffusive aquifer.

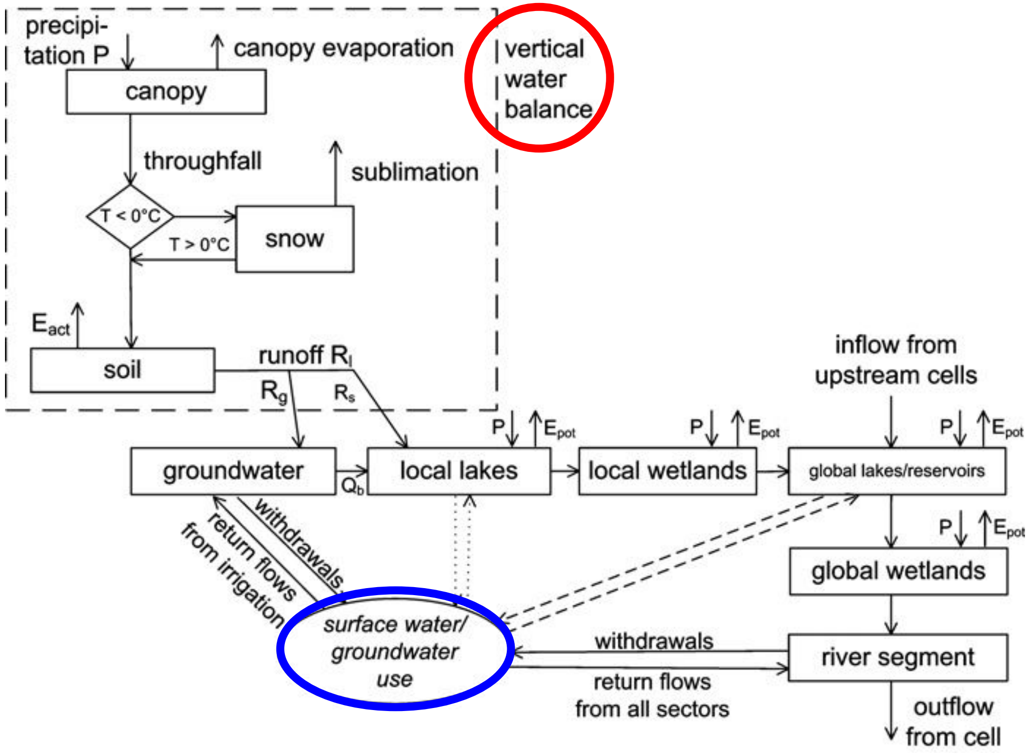


Schematic view of ISBA-CTRIP (Decharme et al., 2019)

Hydrological models

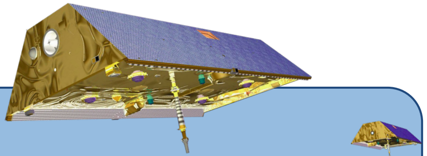
Watergap Global Hydrological Model:

- WGHM solves a **simple vertical water balance**, except for runoff which allows lateral flows from one cell to another
- WGHM takes into account **human influence** on the freshwater storage variability through dams building, water abstraction and irrigation
- Water storage in **glaciers** is included in version 2.2d of WGHM

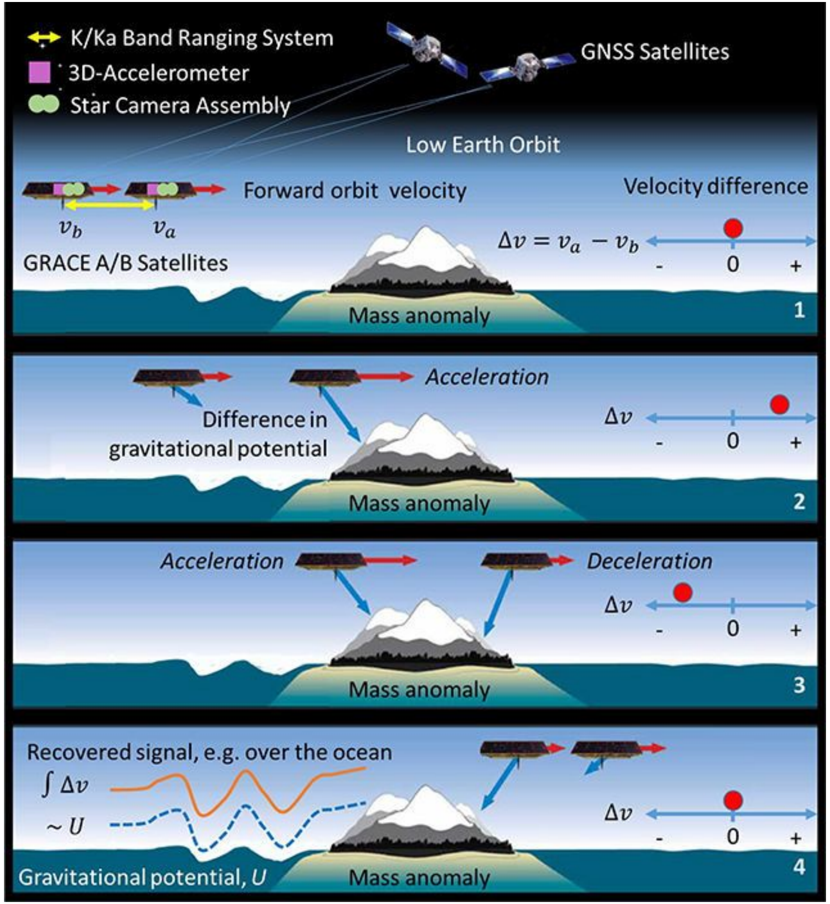


Schematic view of WGHM (Doll et al., 2012)

Concept of the GRACE and GRACE-FO missions

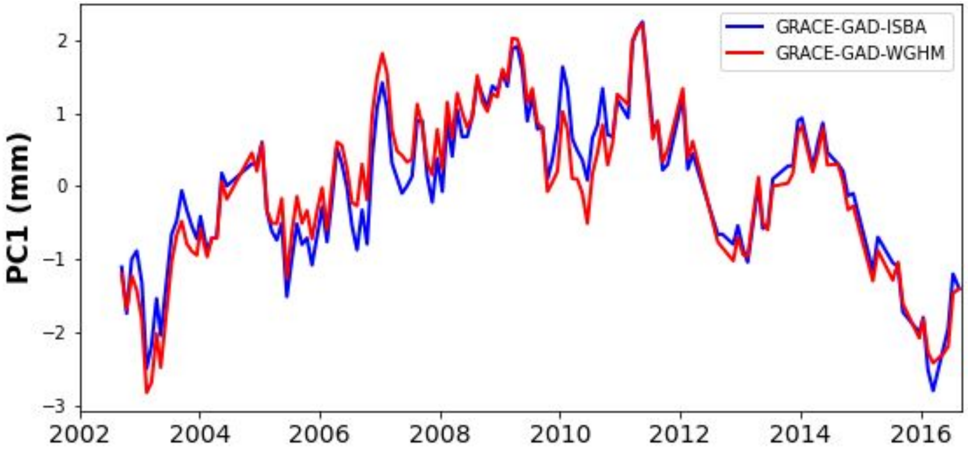


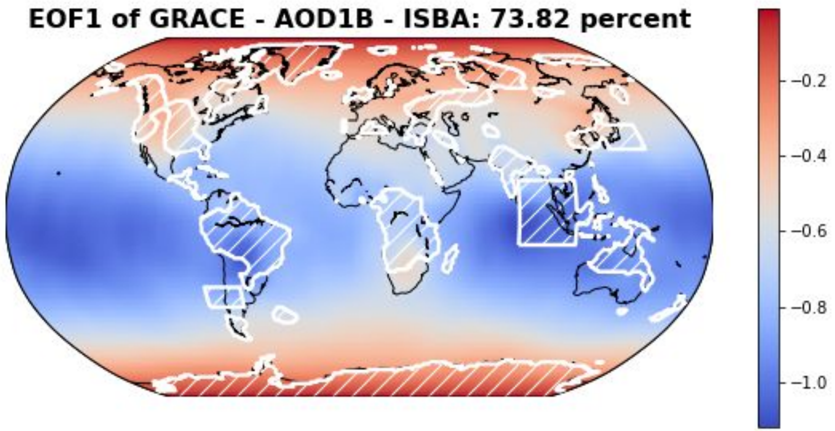
- Partnership NASA/GFZ
- **GRACE** : April 2002 - October 2017
- **GRACE Follow On** : May 2018 - present
- Two identical satellites flying 220 km apart
- Polar orbit ~ 500 km above the Earth
- Provides **time-lapse estimate of the Earth's gravity field**
- Accurate **range (inter-satellite distance) rate** measurement of by microwave ranging system (KBR: 1 µm per second) and laser range interferometry (LRI: 1 nm per second)

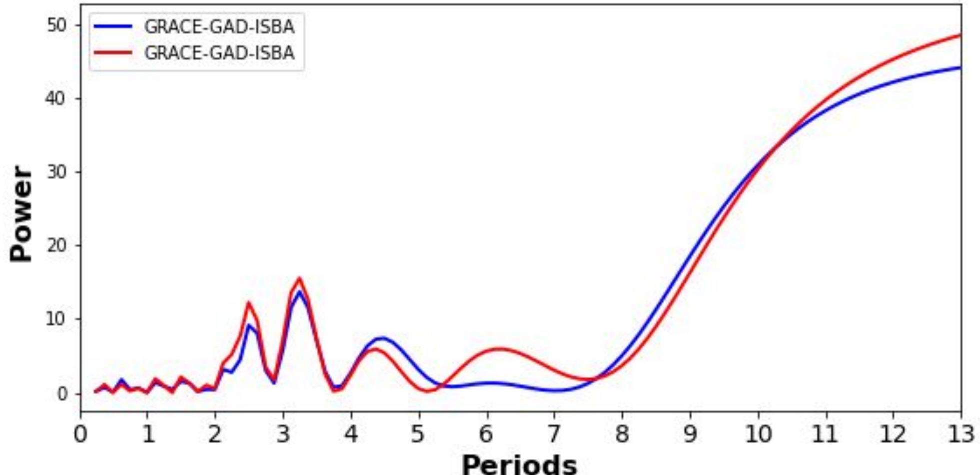


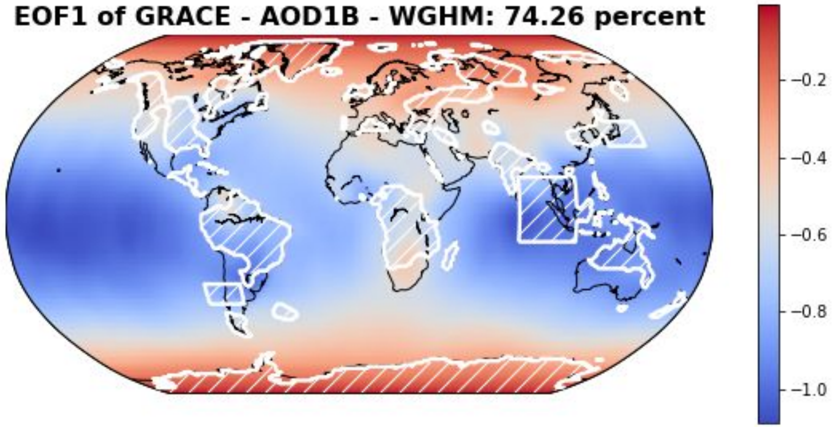
Credit: NASA/JPL-Caltech/GFZ & Tapley et al., 2019, Nature Climate Change

Residual geoid anomalies









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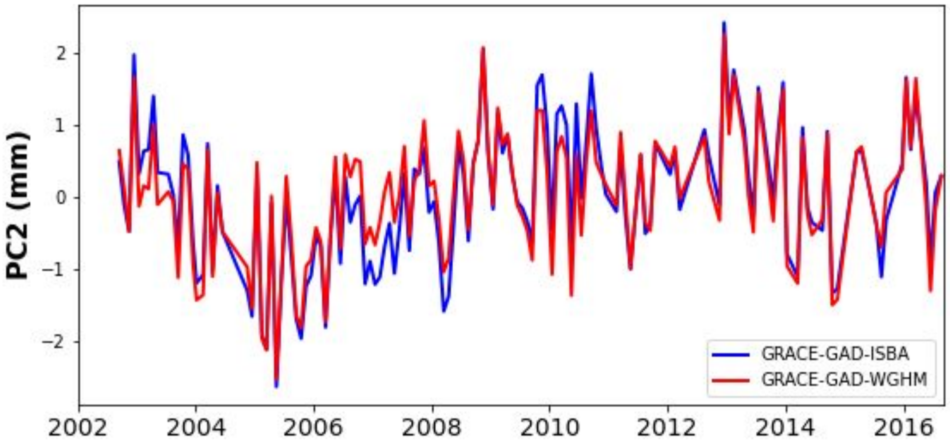

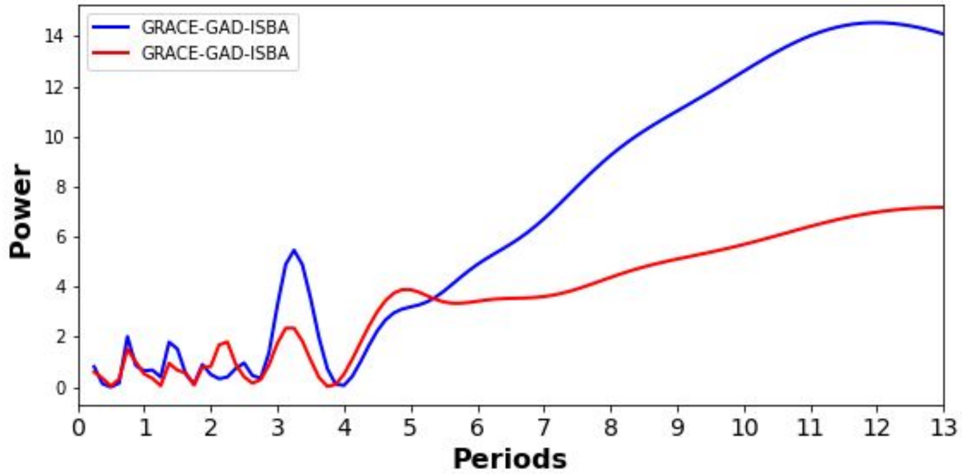

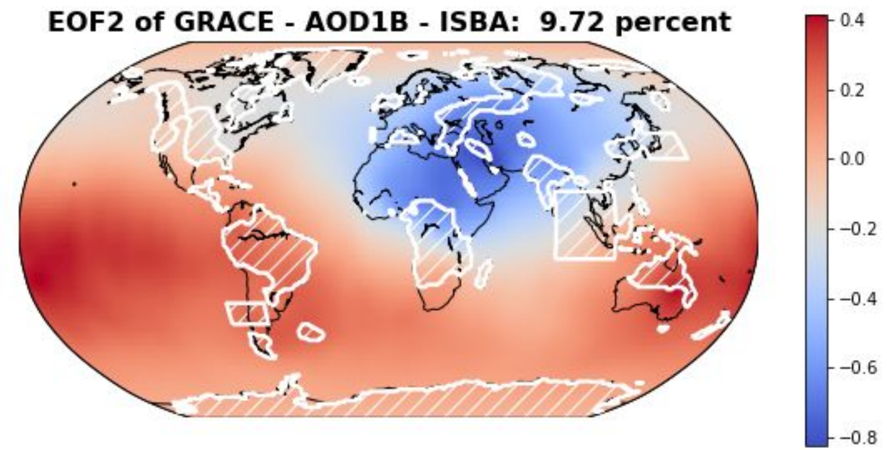

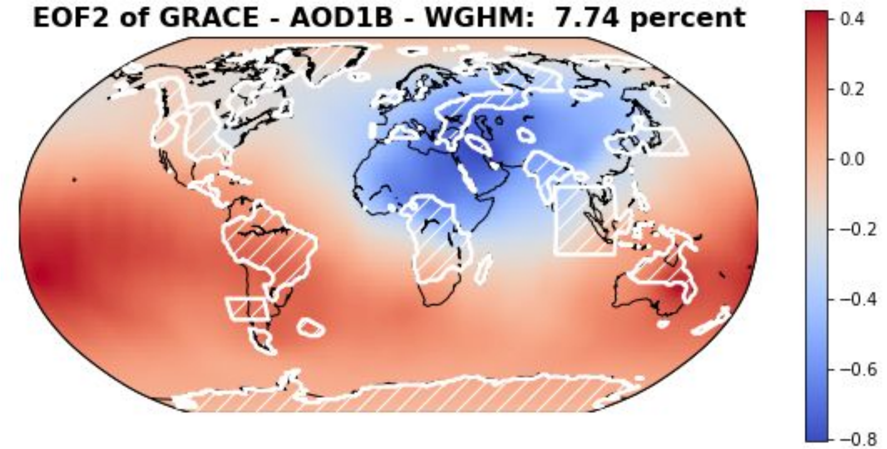

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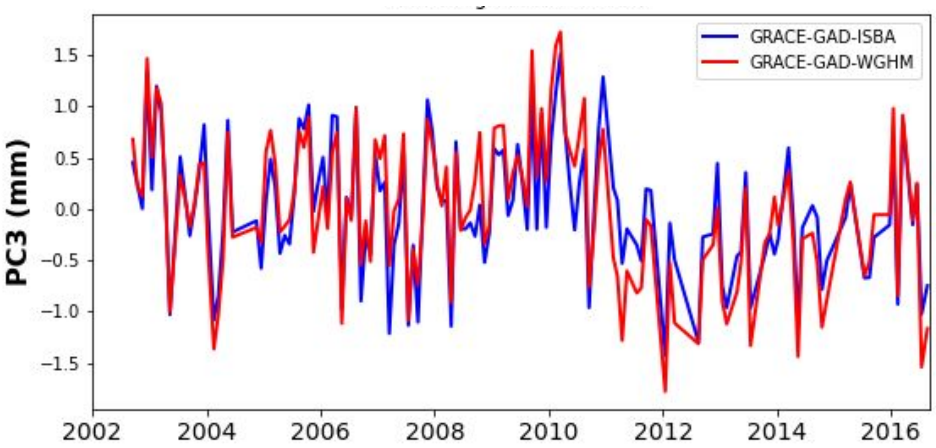
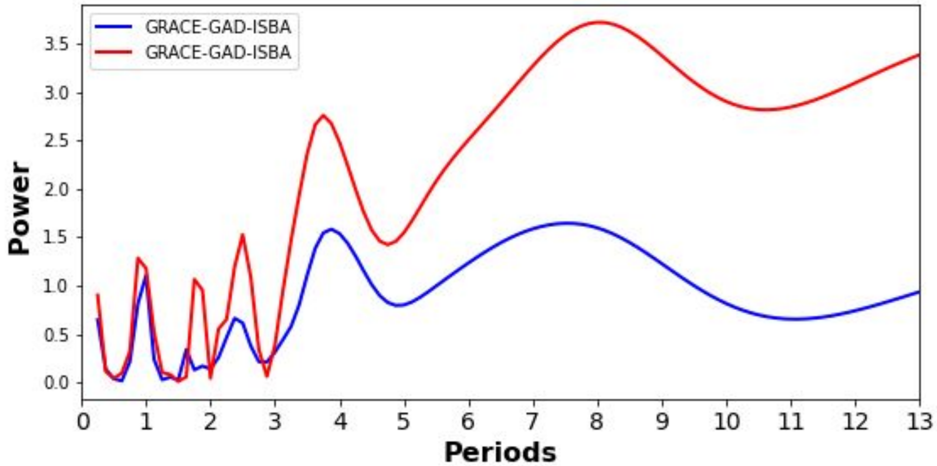
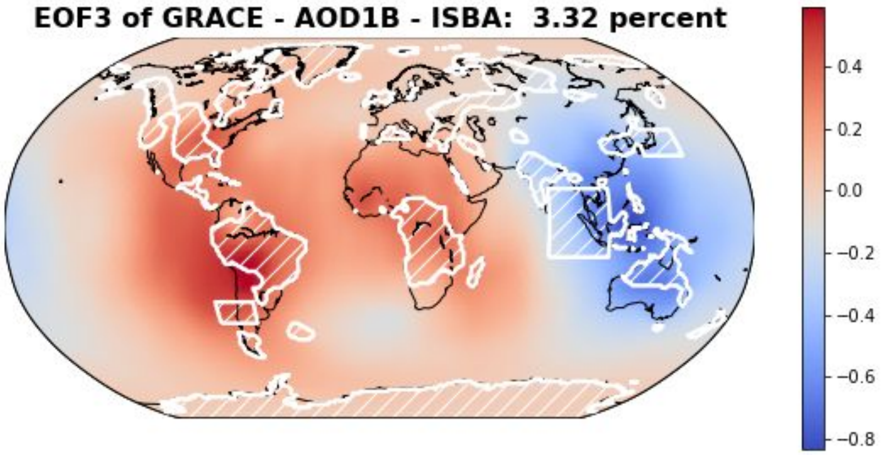
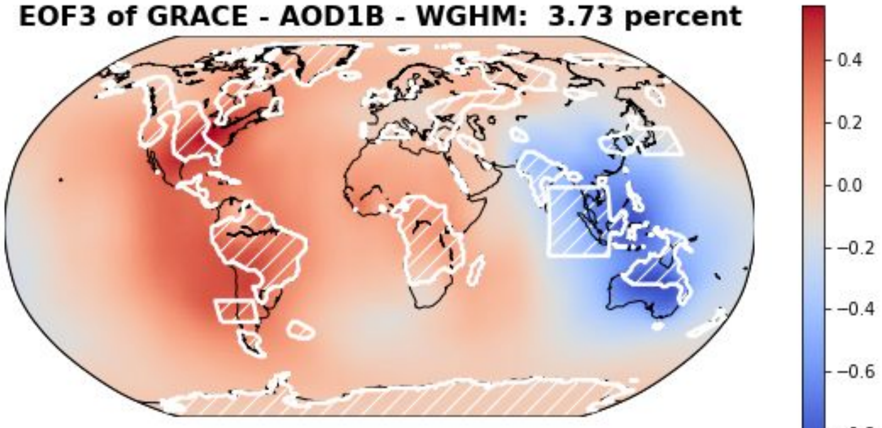
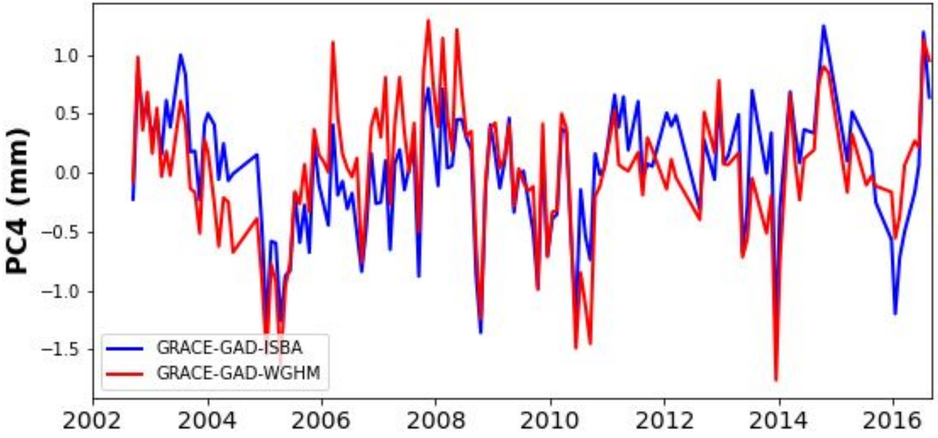


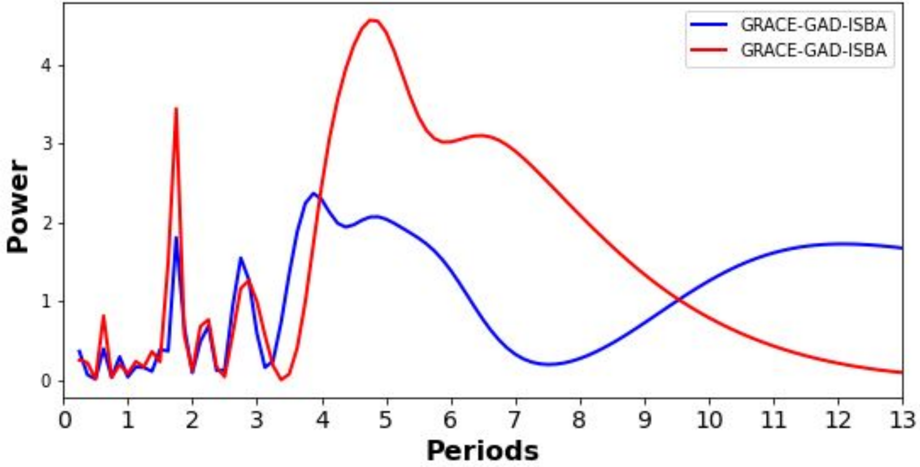


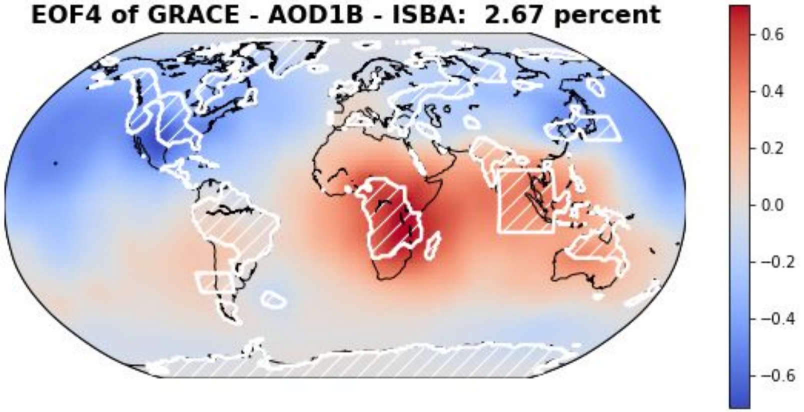


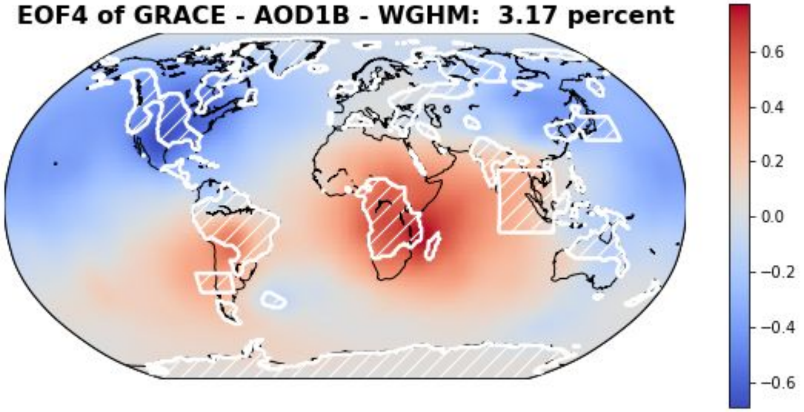


Residual geoid anomalies

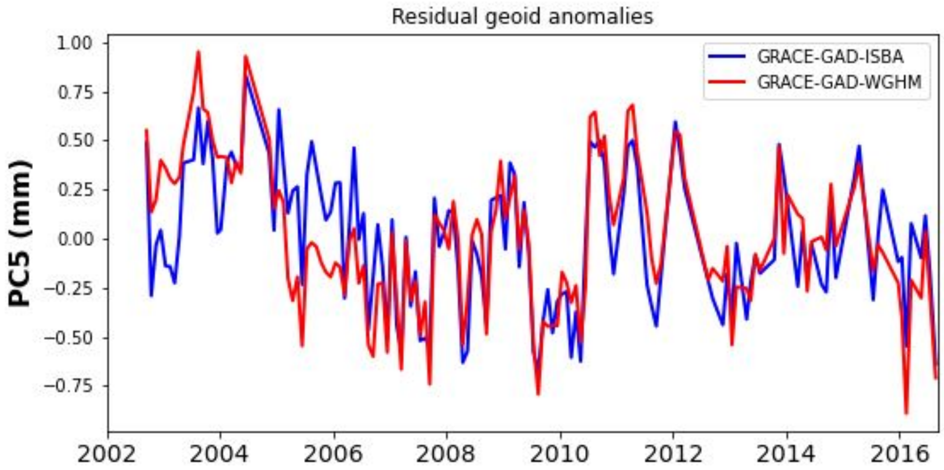


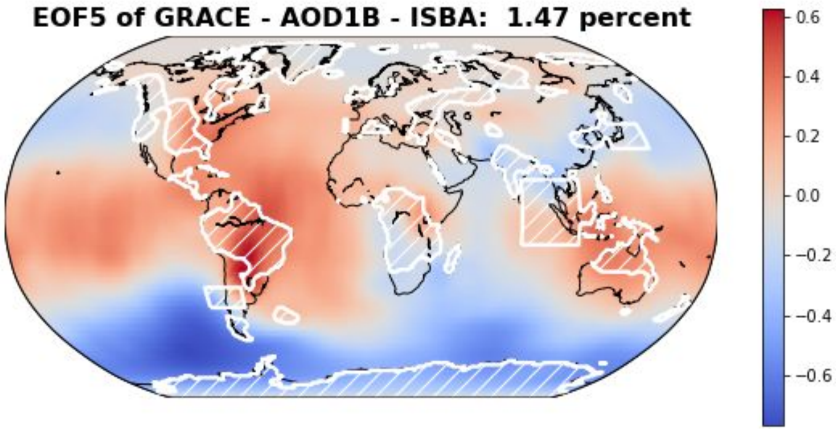


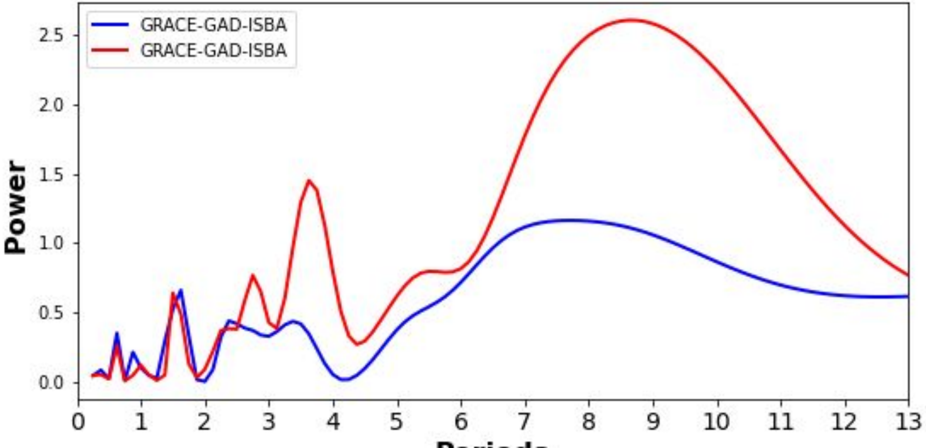


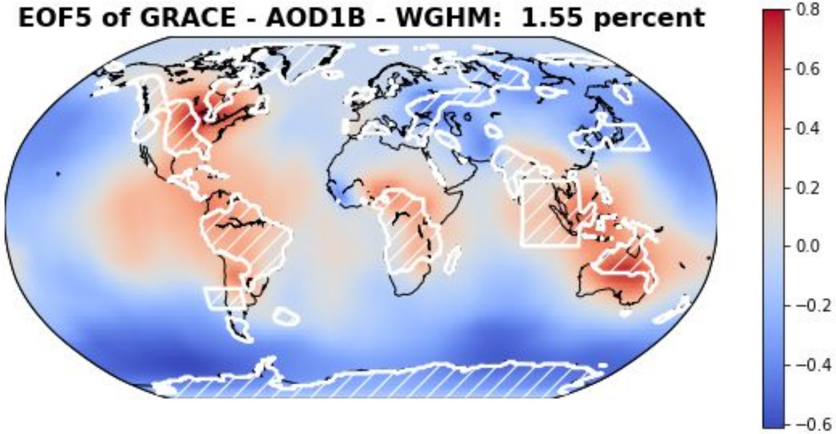


Residual geoid anomalies

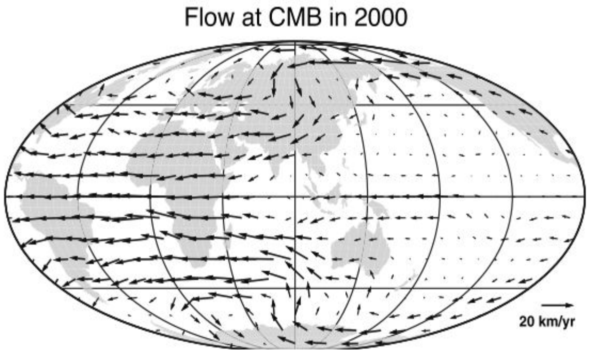








Flow at the CMB

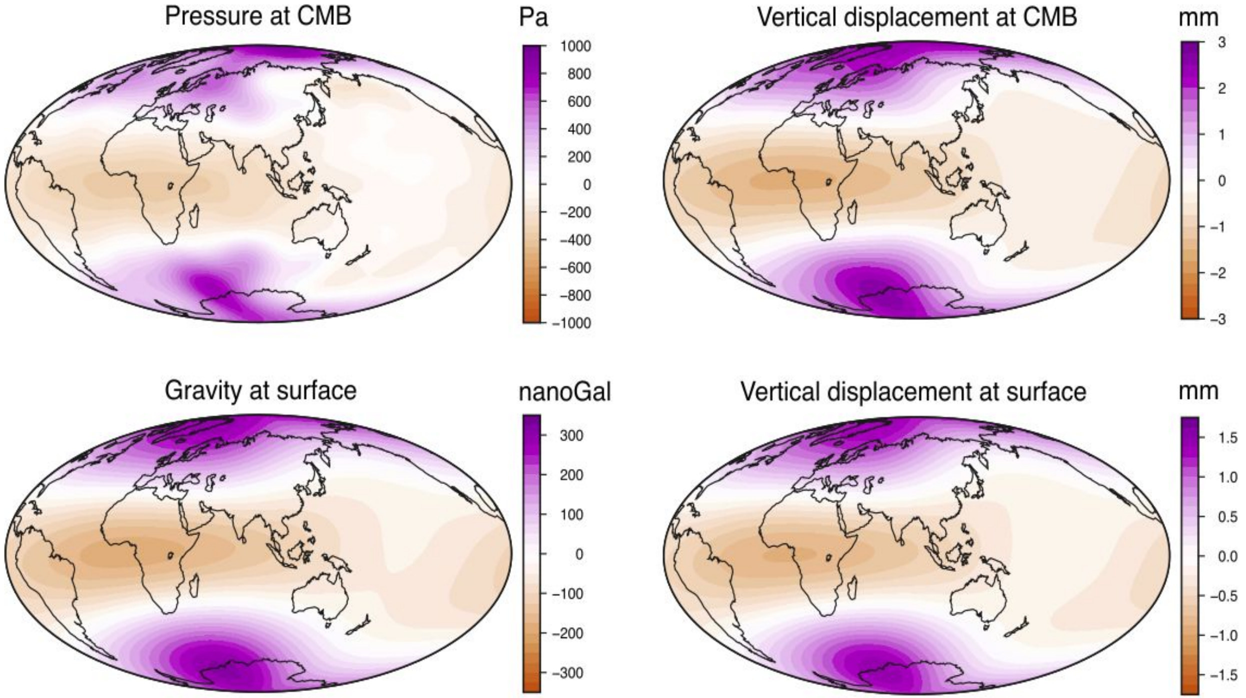


Example of a flow map at the CMB for the year 2000.

The flow model is the ensemble average of the flow models in Barrois et al. (2017) truncated at degree 11

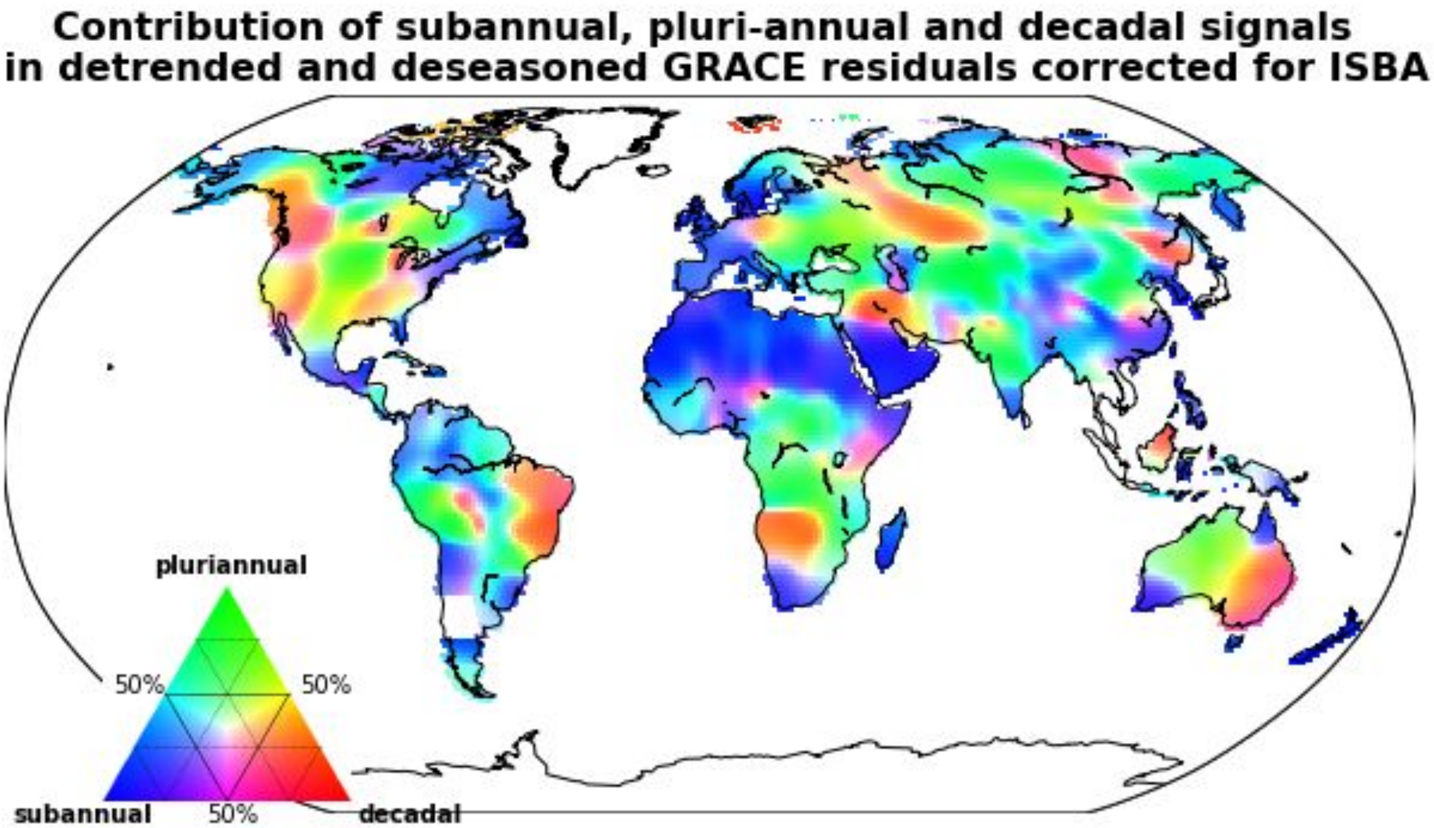
From Dumberry & Mandea (2021)

Surveys in Geophysics
[10.1007/s10712-021-09656-2](https://doi.org/10.1007/s10712-021-09656-2)



Geostrophic pressure, vertical displacement at the CMB and at the surface, and gravity change at the surface associated with the flow at the CMB in 2000.

Residual hydrology signals



Residual hydrology signals