

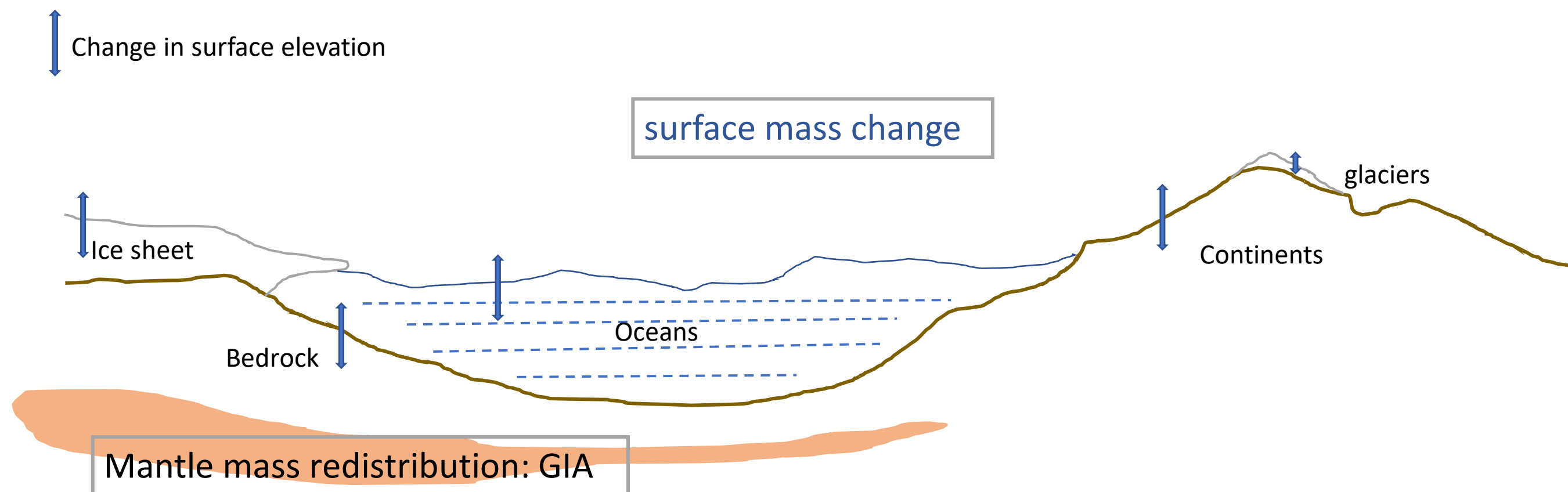


A novel data-driven method to estimate GIA signal from Earth observation data

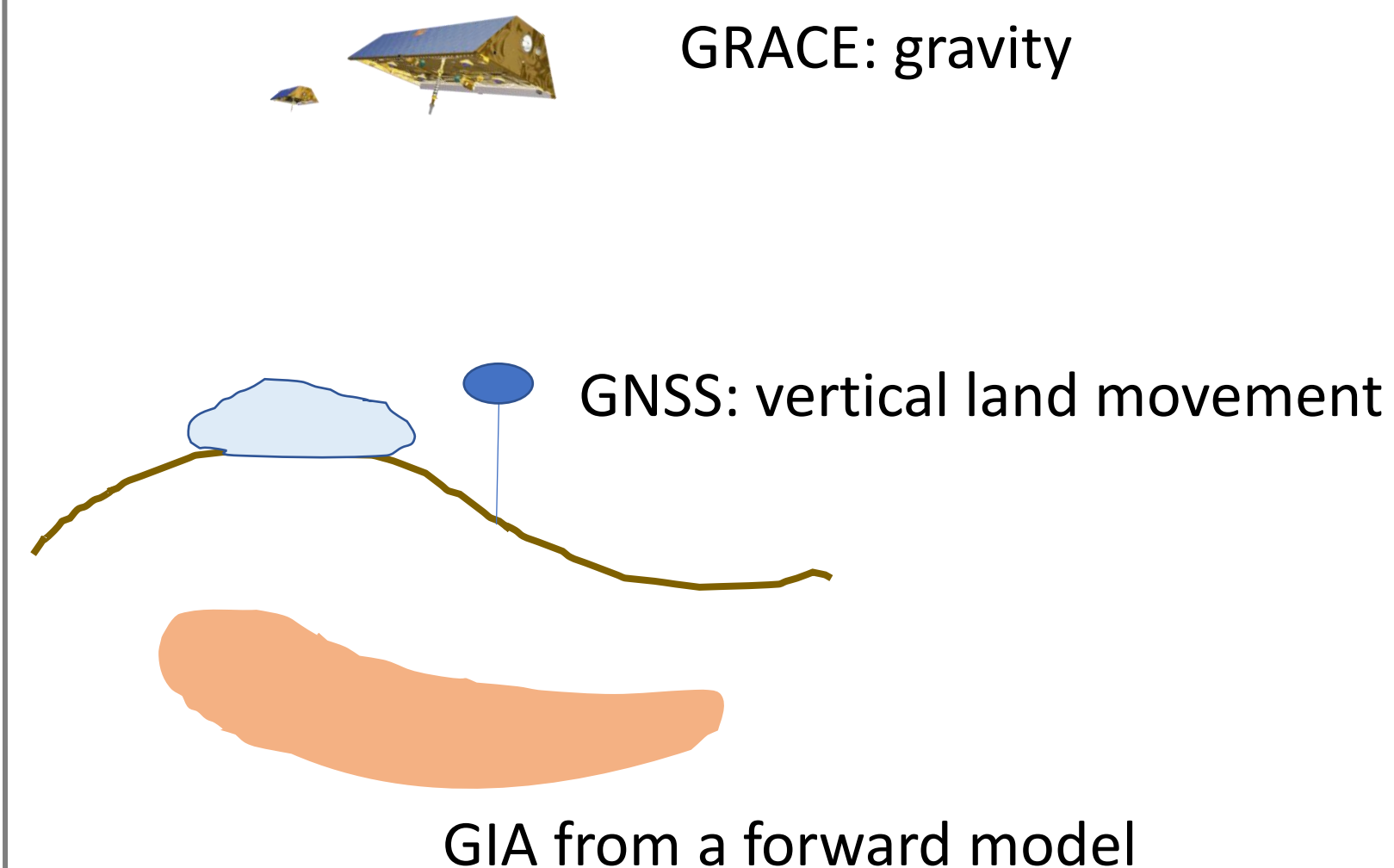
B. D. Vishwakarma, Y. Ziegler, J. L. Bamber, S. Royston



Signals from the present and the past:



Observations!



GIA models → uncertain!

GIA = convolution integral (ice-load history, Earth rheology)

Ice-load history is highly uncertain
Earth models are approximate

The GIA from forward models have high uncertainty!

Data-driven GIA estimates

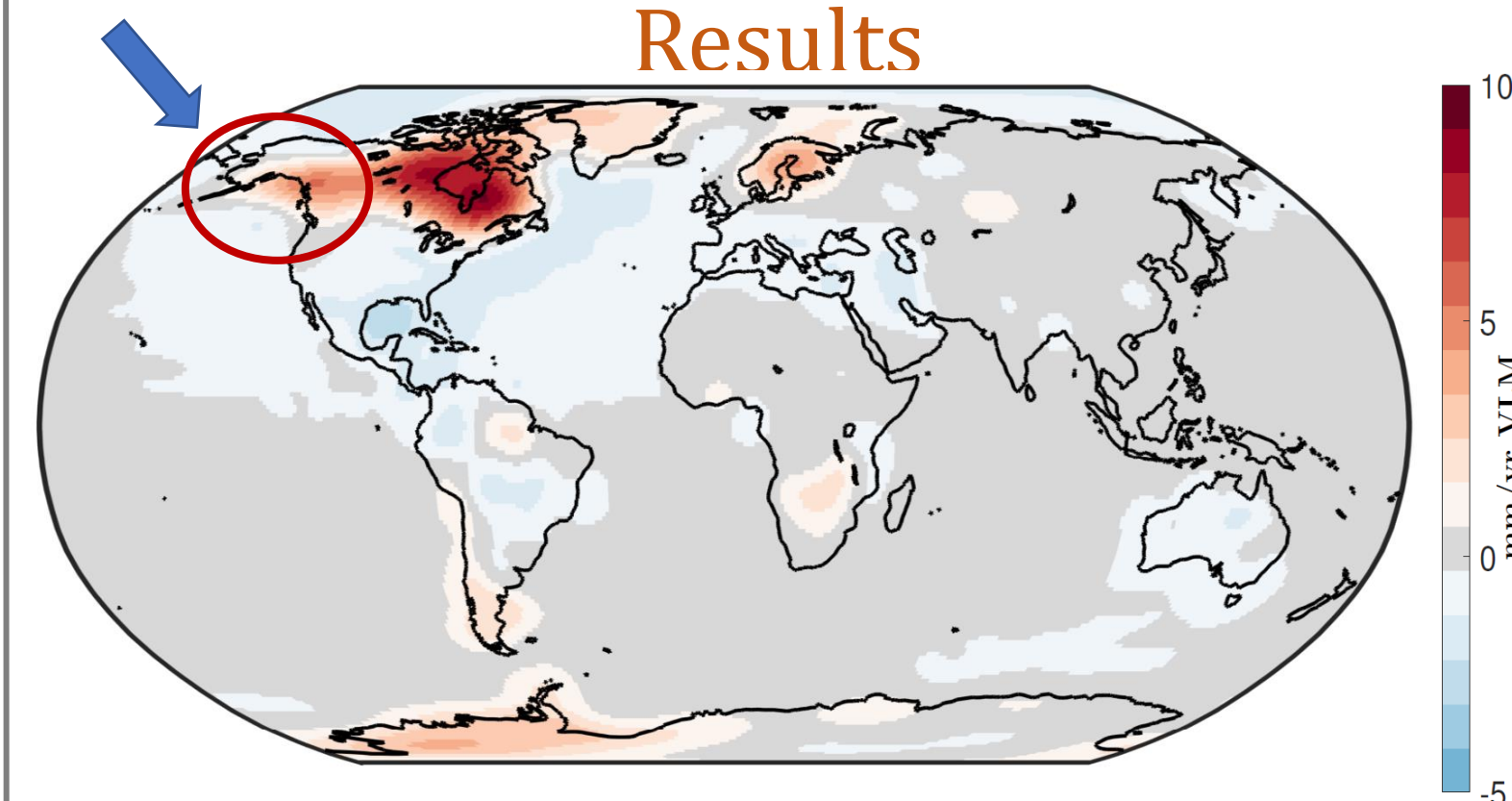
$$\text{GNSS} = f(\text{mass}) + F(\text{GIA})$$

$$\text{GRACE} = g(\text{mass}) + G(\text{GIA})$$

≈ 6000 GNSS time series

GRACE time series

Results

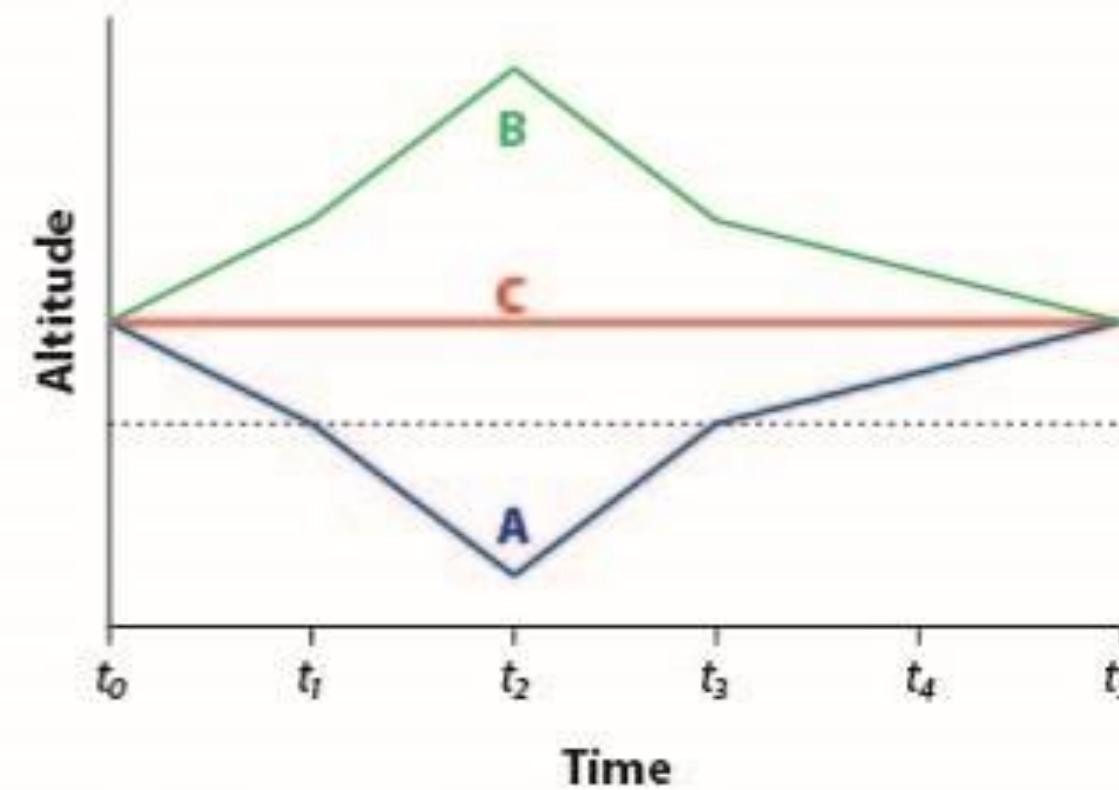
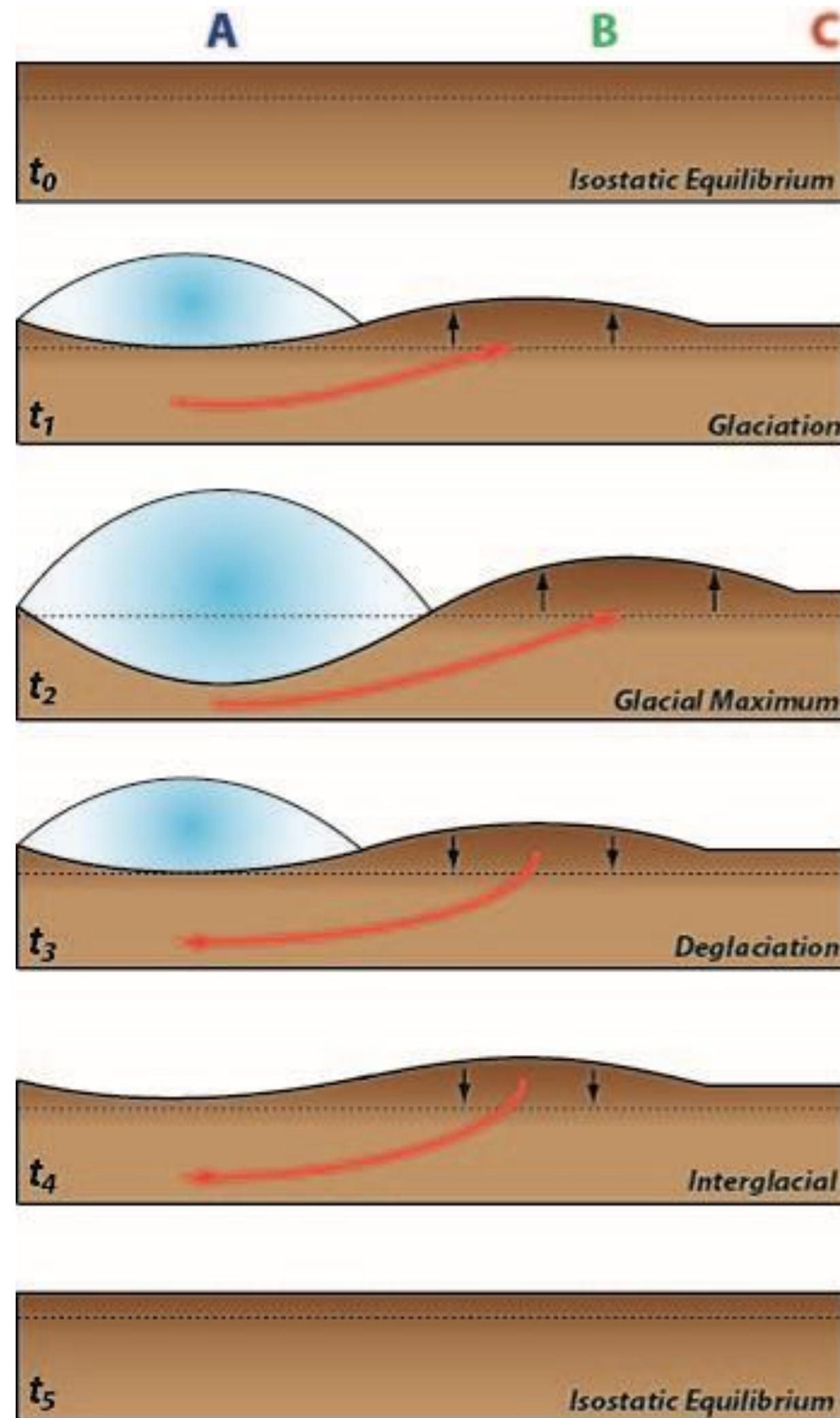


A novel data-driven method to estimate GIA signal from Earth observation data

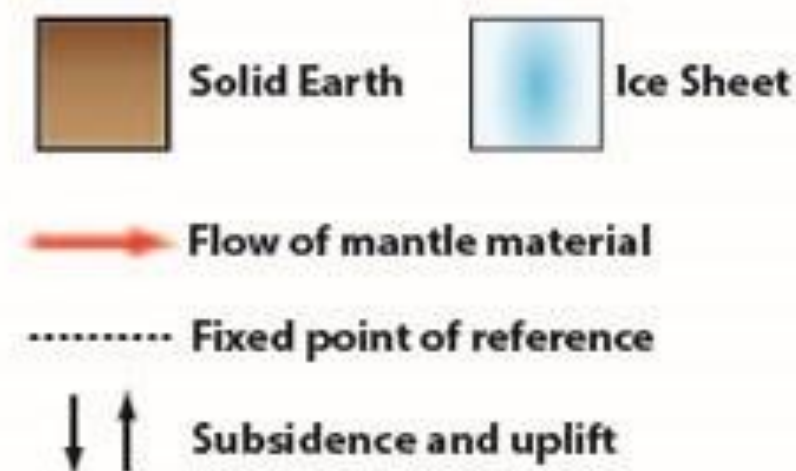
B. D. Vishwakarma¹, Y. Ziegler¹, J. L. Bamber¹, S. Royston¹

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Glacial isostatic adjustment:



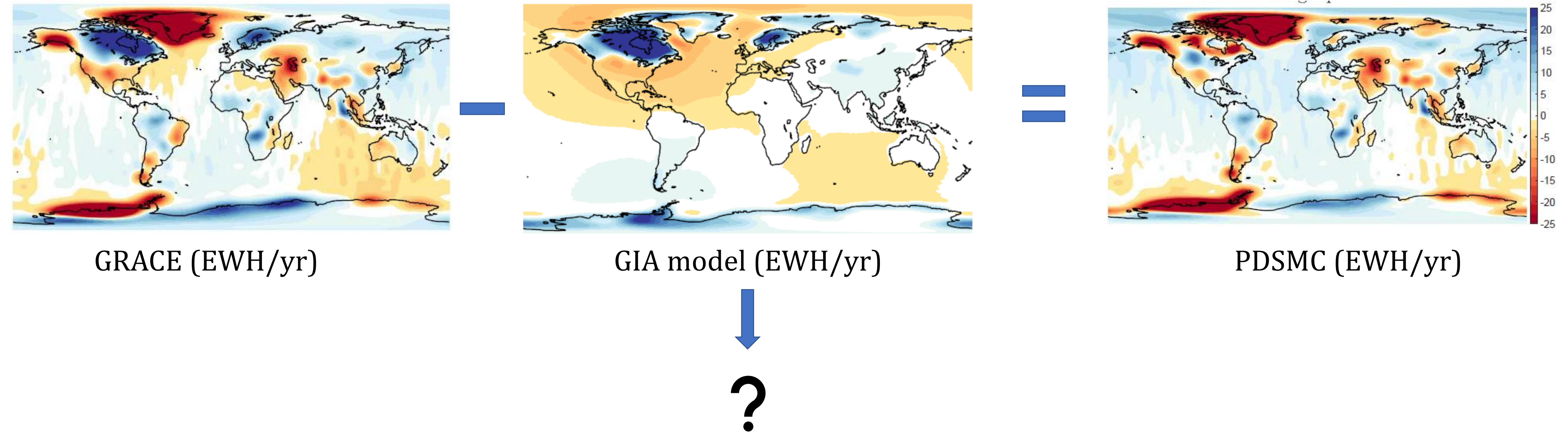
A = near field (e.g. Canada)
B = intermediate field (e.g. Mid Atlantic, USA)
C = far field (e.g. Brazil)



GIA is the visco-elastic response of the solid Earth to the past glacial cycles. The contemporary Earth observation data contains signatures of GIA: for example in gravimetry data (mantle mass redistribution) and in GNSS data (vertical land movement).

These datasets (GRACE and GNSS network) are heavily used for studying climate change, water cycle, and solid Earth processes. Therefore, GIA signal should be carefully removed to obtain realistic impression of other ongoing processes.

GIA estimates removed from GRACE to get present day surface mass change



Usual approach is to use predictions from a forward GIA model

GRACE based estimates of ice-sheet mass balance, sea level rise, and hydrological budget (over some regions) are therefore sensitive to the accuracy of GIA.

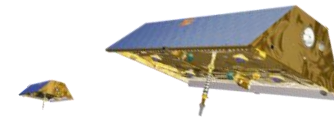
GIA forward models are uncertain

- GIA models rely on **past ice-load history** and approximate **Earth rheology**.

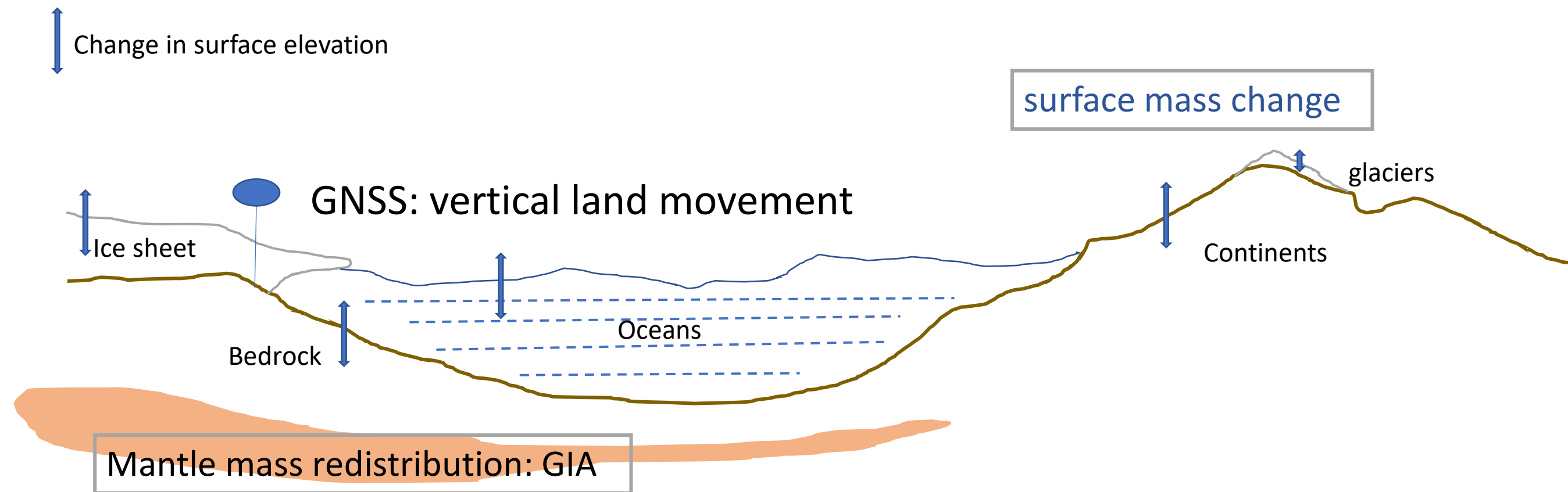
Hence data-driven GIA estimates have become popular

- Before the launch of GRACE satellite mission, possibility of obtaining GIA from GRACE and altimetry data were hypothesized (see Wahr et al., 2000, Riva et al., 2009).
- This signal separation is not easy as the quantities observed by various observation systems are related to GIA and PDSMC differently (to know more attend the vPICO by Y. Ziegler [G3.1/CL5.1.10](#) on Thursday 9:30 CEST)

Our framework



GRACE: gravity



- Total VLM observed by GNSS:

$$\Delta u(t) = \Delta u_e(t) + \Delta u_v(t).$$

- u_e : elastic VLM due to PDSMC
- u_v : GIA driven VLM

$$\Delta u_e = f(\text{PDSMC})$$

$$\Delta u_v = g(\text{GIA mantle mass redis.})$$

Rate of GRACE observed potential change = rate of PDSMC potential change + rate of GIA potential change

$$\Delta \dot{u}_e(\theta, \lambda) = R \sum_{\ell, m} \frac{h'_\ell}{1 + k'_\ell} \tilde{P}_{\ell m}(\cos \theta) \left[\Delta \dot{C}_{\ell m}^p \cos(m\lambda) + \Delta \dot{S}_{\ell m}^p \sin(m\lambda) \right]$$

Davis et al., 2004

$$\Delta \dot{u}_v(\theta, \lambda) = R \sum_{\ell, m} (1.1677\ell - 0.5233) \tilde{P}_{\ell m}(\cos \theta) \left[\Delta \dot{C}_{\ell m}^G \cos(m\lambda) + \Delta \dot{S}_{\ell m}^G \sin(m\lambda) \right]$$

Purcell et al., 2012

Adding equation for Δu_e and Δu_v gives us the total VLM

Our framework

Adding and subtracting $\sum_{\ell,m} \frac{h'_\ell}{1+k'_\ell} \tilde{P}_{\ell m}(\cos \theta) \left[\Delta \dot{C}_{\ell m}^G \cos(m\lambda) + \Delta \dot{S}_{\ell m}^G \sin(m\lambda) \right]$ from the last eqn, and rearranging:

$$\Delta \dot{u}(\cdot) = R \sum_{\ell,m} \left\{ \frac{h'_\ell}{1+k'_\ell} \tilde{P}_{\ell m}(\cos \theta) \left[\left(\Delta \dot{C}_{\ell m}^p + \Delta \dot{C}_{\ell m}^G \right) \cos(m\lambda) + \left(\Delta \dot{S}_{\ell m}^p + \Delta \dot{C}_{\ell m}^G \right) \sin(m\lambda) \right] \right. \\ \left. + \left(1.1677\ell - 0.5233 - \frac{h'_\ell}{1+k'_\ell} \right) \tilde{P}_{\ell m}(\cos \theta) \left[\Delta \dot{C}_{\ell m}^G \cos(m\lambda) + \Delta \dot{S}_{\ell m}^G \sin(m\lambda) \right] \right\}.$$

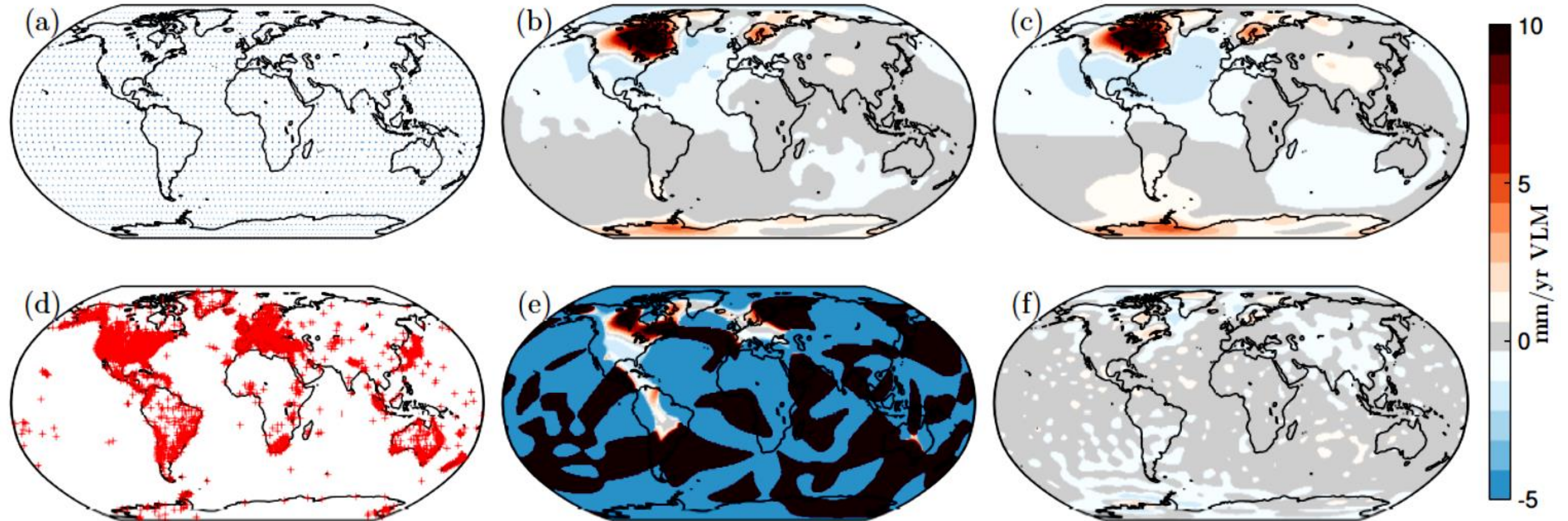
Where $\left(\Delta \dot{C}_{\ell m}^p + \Delta \dot{C}_{\ell m}^G \right)$ is available from GRACE and the right hand side is available from GNSS.

This can be written as a least squares problem and solved!

Assumptions:

1. GNSS observations observe only the sum of GIA and elastic signal due to PDSMC
To achieve this the NGL GNSS dataset was tested and filtered rigorously to choose approx. 6000 stations only
2. The relations used are accurate enough to represent relation between respective gravitational potential and VLM
We have used the relation from Purcell et al., 2012 instead of Wahr et al., 2000 or 1995.

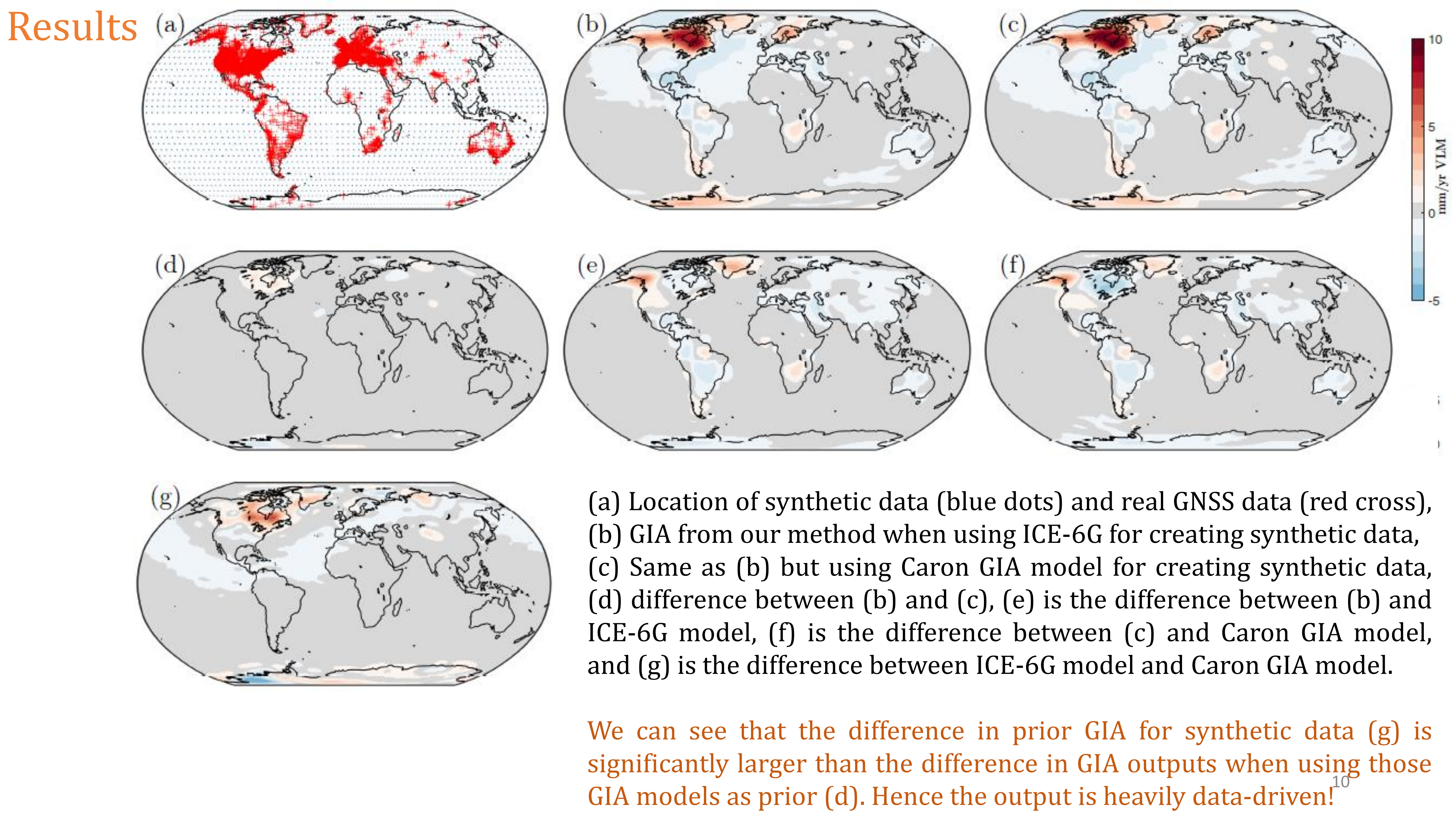
Synthetic experiment



The synthetic data is prepared combining the VLM from ICE-6G GIA model, the elastic VLM from (GRACE-ICE 6G), and a random white noise with values between ± 1 mm/yr . (a) Ideal case GNSS network, where each blue dot represent a GNSS station with data available from 2005 to 2015. (b) GIA solution using our framework, (c) truth or the GIA model used in preparing the synthetic data. (d) location of GNSS network in reality, (e) the GIA obtained with synthetic data for locations shown in (d). (f) shows the difference between (b) and (c).

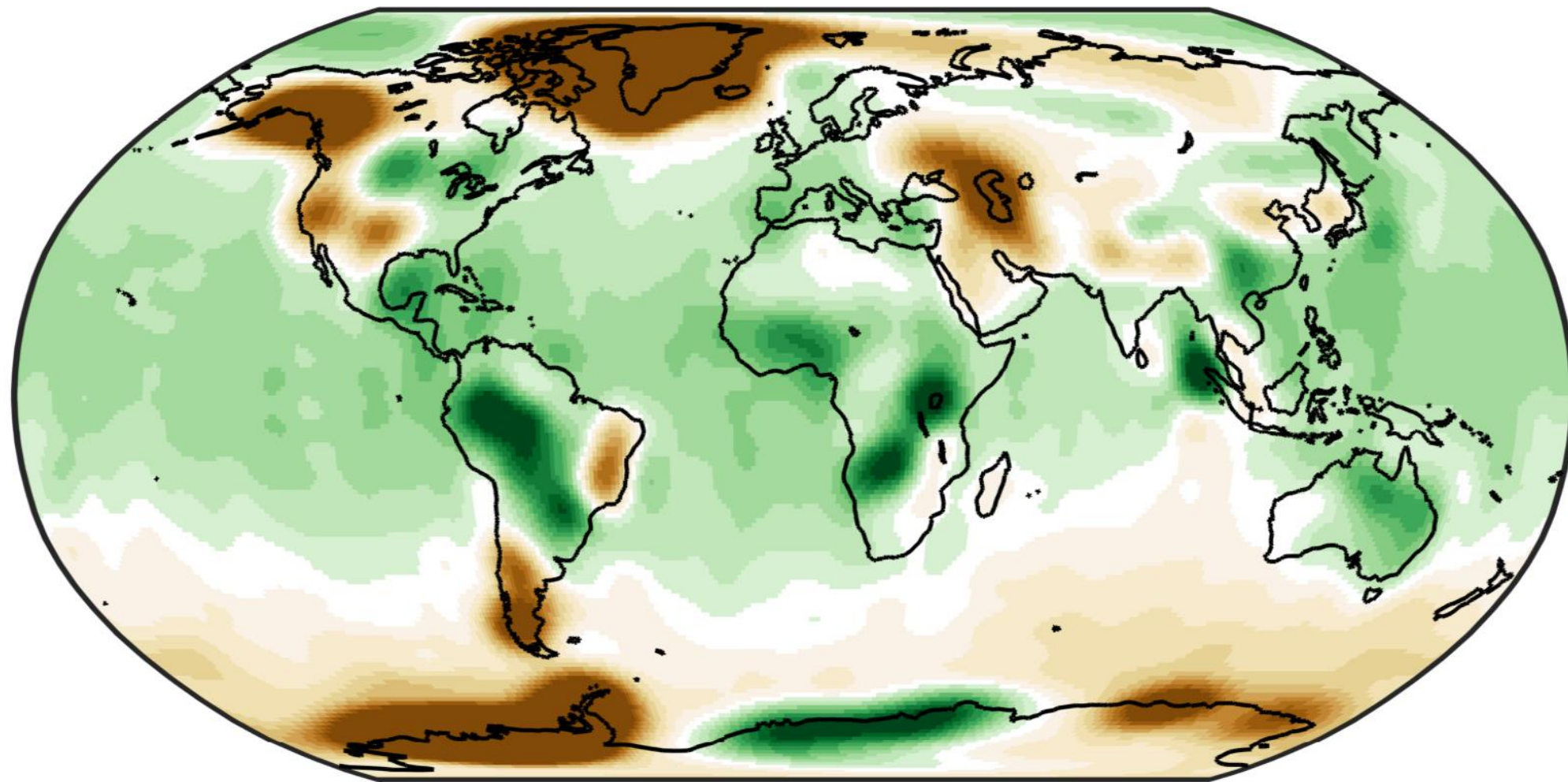
Gaps in data!

- Spatial gaps in NGL GNSS network is affecting the framework and is the biggest stumbling block.
- We counter this challenge by augmenting real GNSS data with synthetic data only in gaps: We check if there is a GNSS station in a $5^{\circ} \times 5^{\circ}$ box, if not we place a synthetic GNSS station at the centre of the $5^{\circ} \times 5^{\circ}$ grid cell.
- This augmentation is equivalent to providing a prior information for locations where we do not have data.
- Since most of the GIA dominated regions (North America and the Europe) have excellent GNSS coverage, we can assume that output from the framework will be data-driven in those regions.
- We can revert the framework and aim at determining the PDSMC stokes coefficient.
- If we get similar GIA and PDSMC estimates when using different GIA models for creating synthetic data, we can be confident that the
- If the PDSMC from our framework is similar to contemporary knowledge of water mass change and GIA, we can be confident that the output from the framework can be trusted.

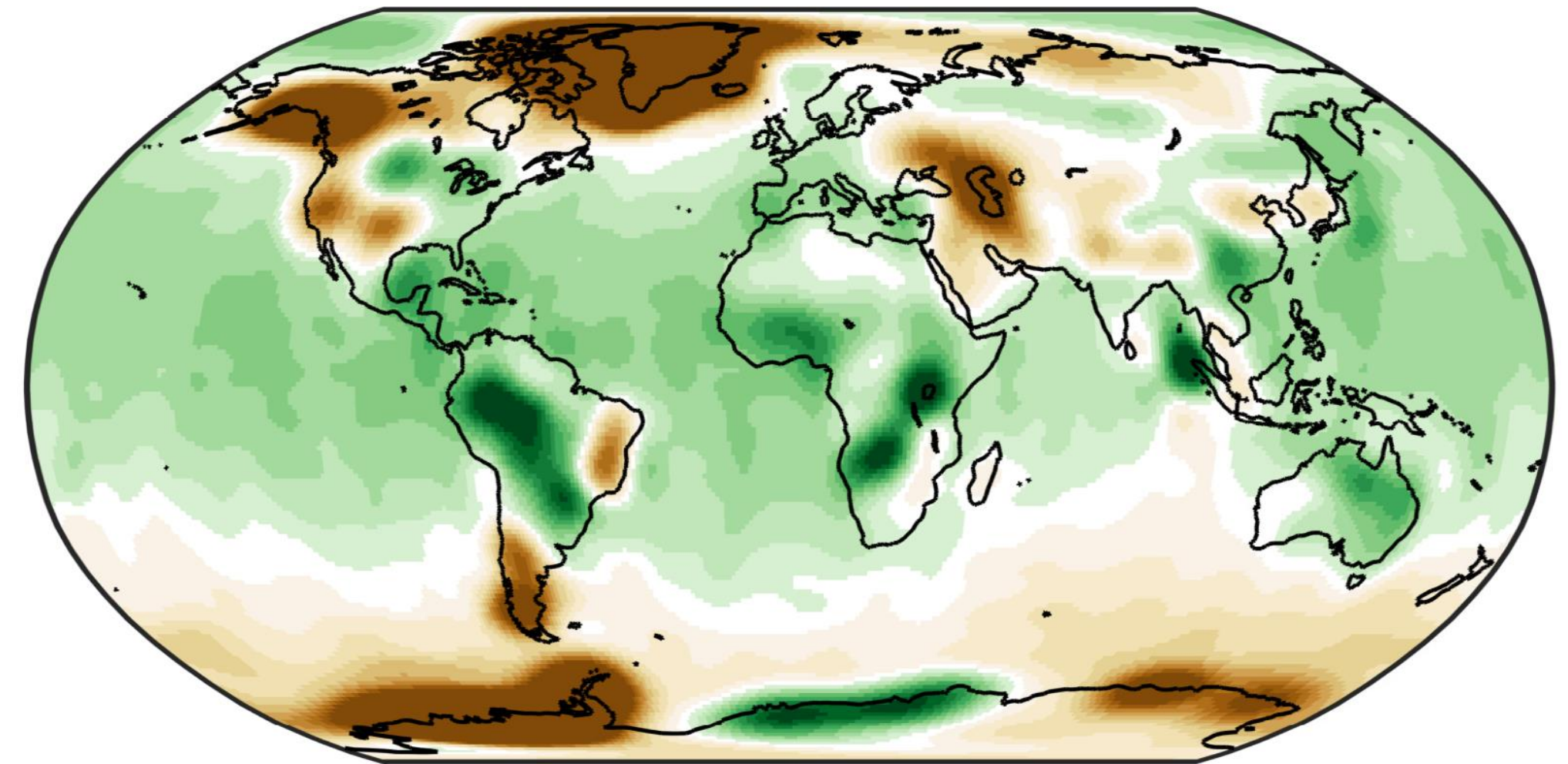


Using the framework to obtain present day surface mass trends:

PDSMC when using ICE-6G GIA model as prior



PDSMC when using Caron GIA model as prior

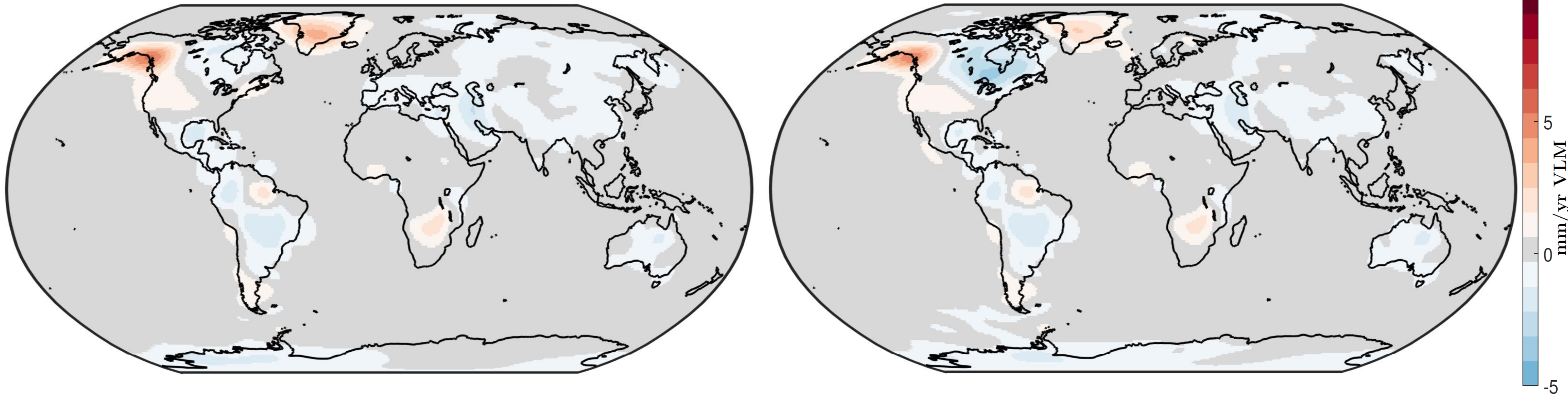


The mass change trends are coherent with other estimates: mass loss in Caspian sea, middle East, Western-USA, India, Alaska, Greenland, west-Antarctica, and mass gain over Eastern-USA, Amazon, Africa, East Antarctica, Australia and China (three gorges Dam).

Updates on GIA

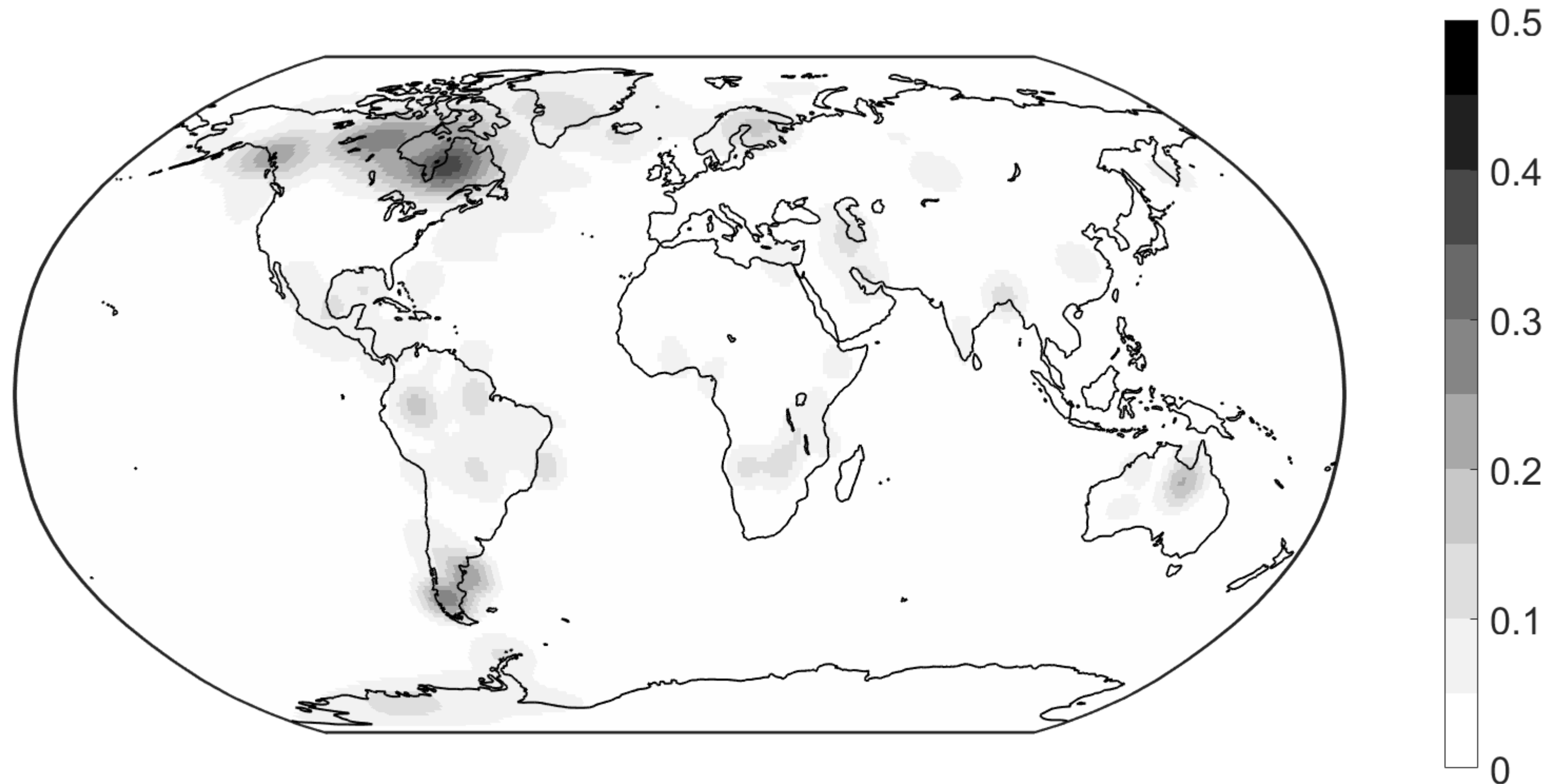
Diff between our GIA and ICE-6G GIA

Diff between our GIA and Caron GIA model



We can trust our GIA estimate over regions with good GNSS coverage. Our GIA estimate differs significantly from both the GIA models over Alaska. We get a GIA signal over other parts of the world (South America, Asia) due to our assumption that GNSS only observed GIA+elastic signal. Over North-America GIA bulge, we find that the ICE-6G model is closer to our estimate w.r.t Caron model. Nevertheless, both the models overestimate GIA in this region. There is no update over Fennoscandia, which means that the GIA models are very robust in this region.

Uncertainty



Uncertainty determined in a Monte-Carlo simulation environment, where the prior GIA models were allowed to vary between 20% of the magnitude and then the GIA outputs were obtained 100 times. The standard deviation of the GIA output is referred to as the uncertainty. Units are mm/yr.

Conclusions and Caveats

- A mathematical framework developed that is able to separate PDSMC and GIA from GRACE and GNSS data
- The method is shown to work in a synthetic closed-loop environment
- When applied to real data, spatial gaps pose a problem that is countered by augmenting real data with synthetic data
- The results are heavily data-driven! (impact of prior is very small)
- We suspect that the currently used GIA models underestimate GIA in Alaska and overestimate over Alaska and Greenland.
- The method relies on assumption that GNSS data observes only the GIA and PDSMC elastic signal, which is not true and any local effects (seismic, geological) would affect the results.
- More GNSS stations and longer time-series would improve the results.
- The relation between potential change due to a process and respective VLM are approximate, which means they are representative of a general behaviour over the globe but local deviations may not be captured (e.g. local viscosity profiles)

Thanks a lot for your attention!

Manuscript, codes, and data submitted to GRL

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