A novel data-driven method to estimate GIA from GPS and GRACE

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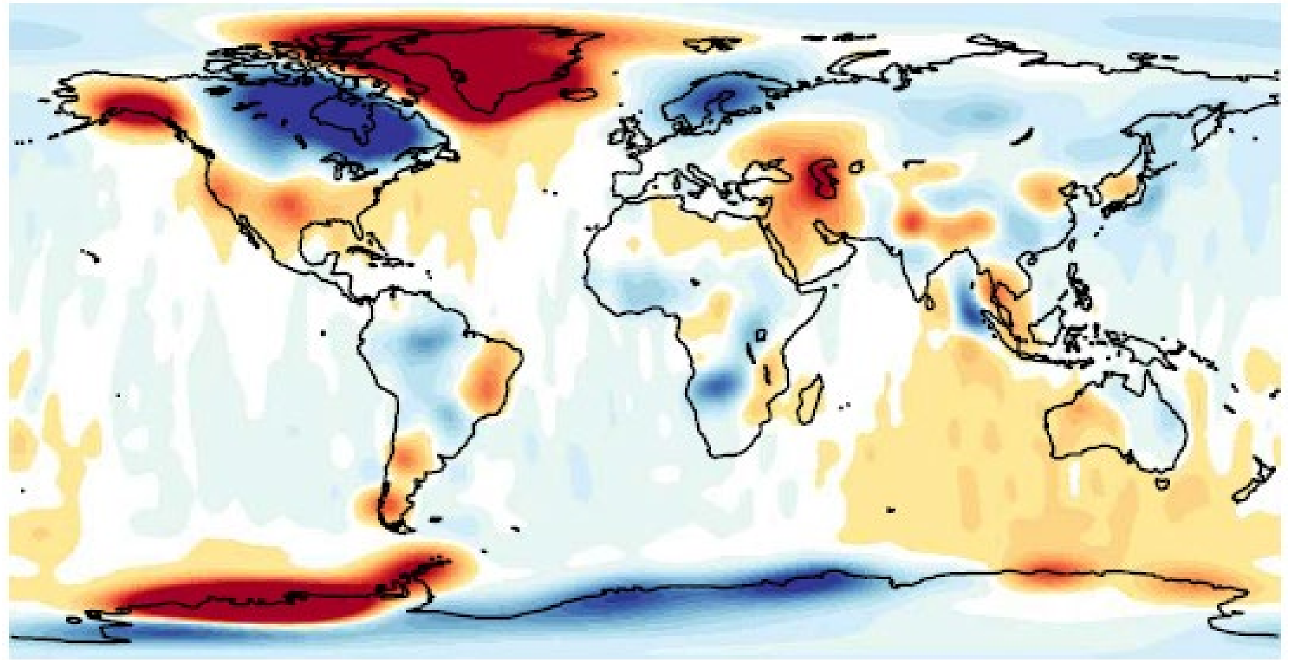
GIA estimates removed from GRACE to get present day surface mass change



GRACE (EWH/yr)

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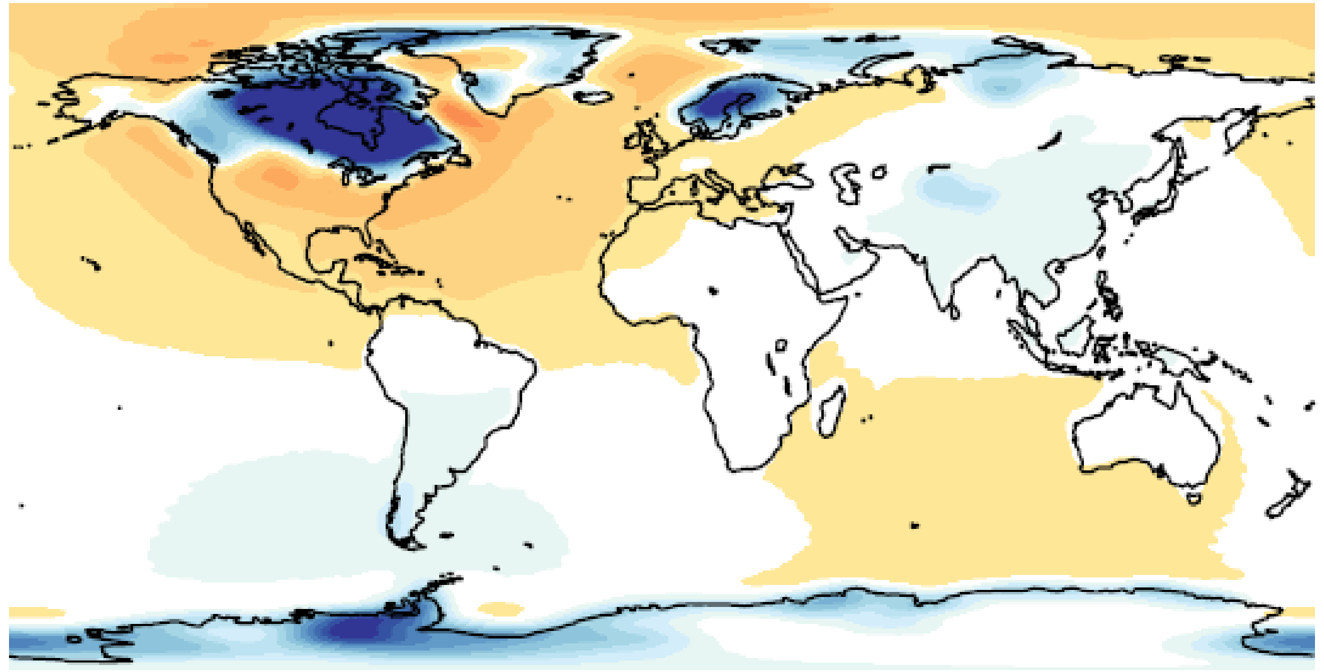

GIA model (EWH/yr)

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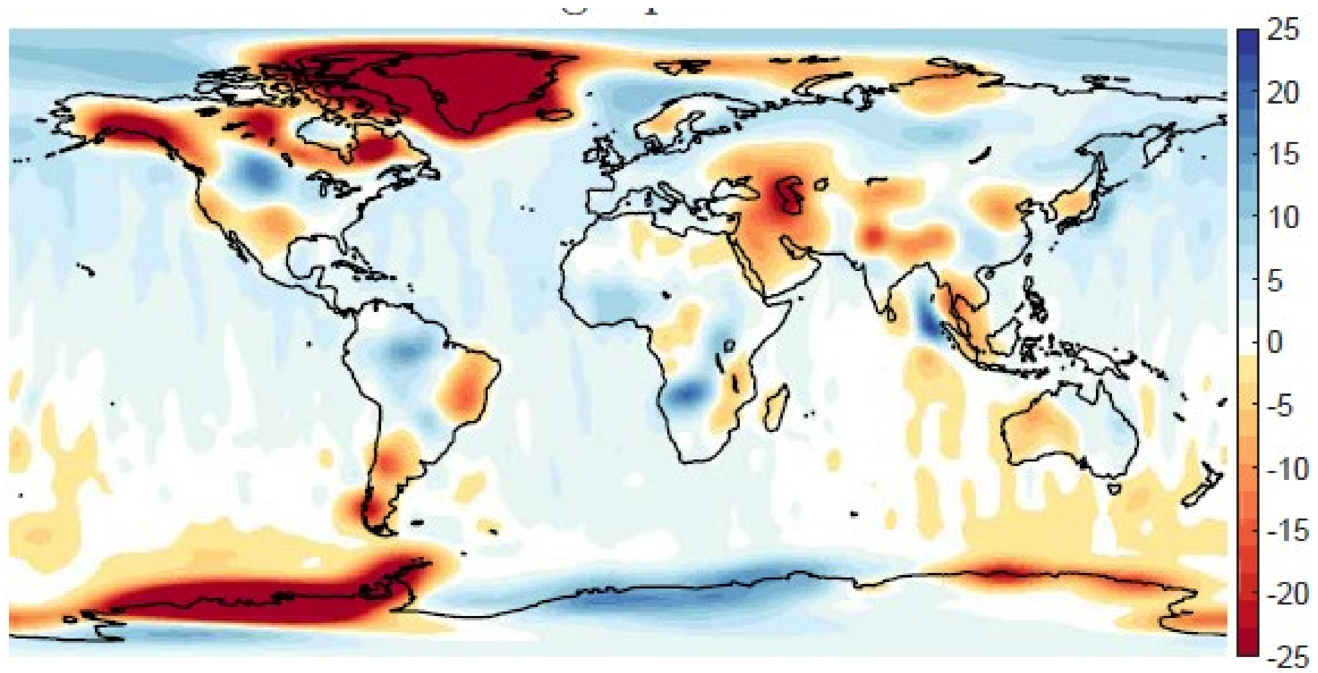


PDSMC (EWH/yr)

?

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

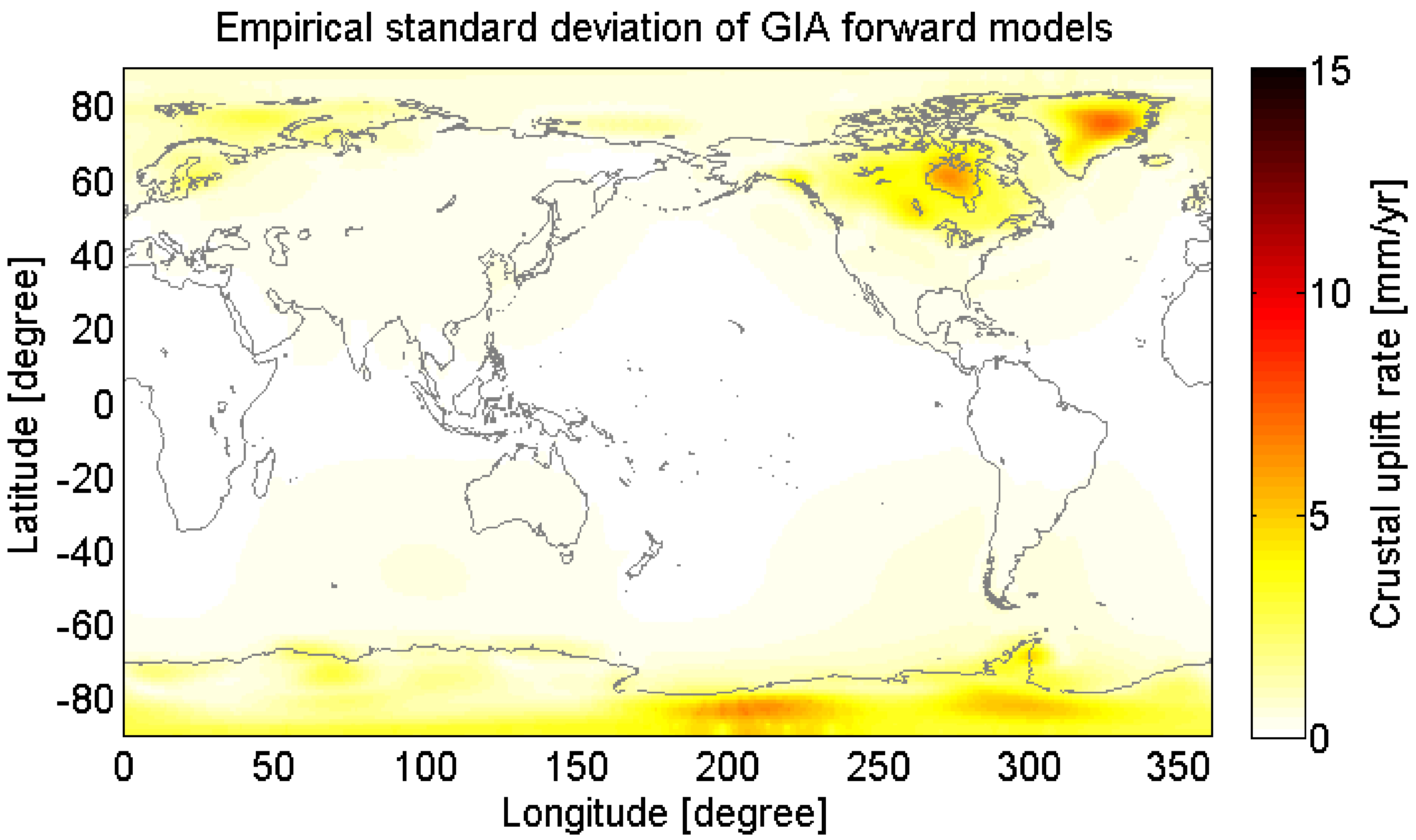
- GIA models rely on past ice-load history and approximate Earth rheology.

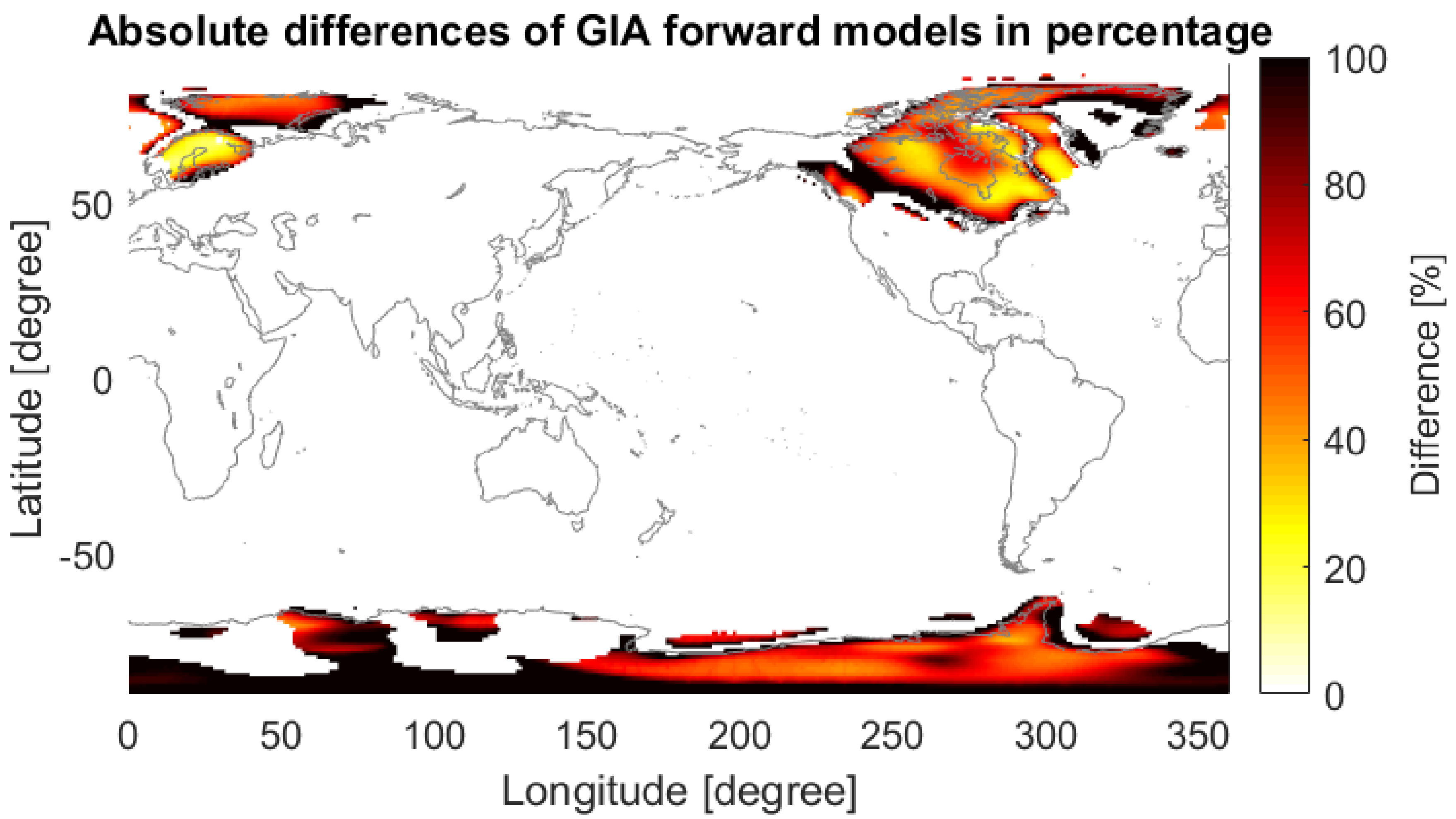
Hence data-driven GIA estimates have become popular

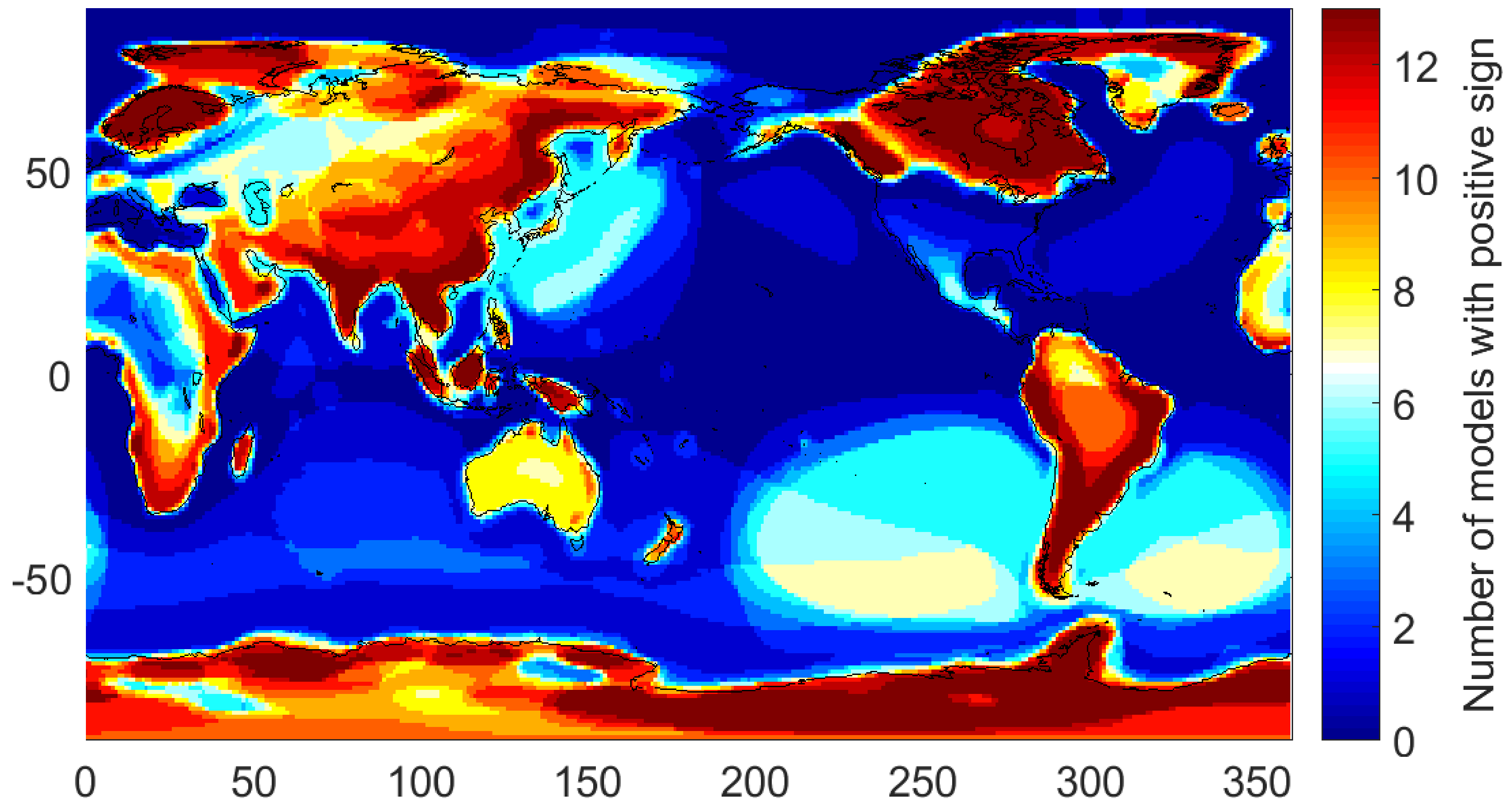
- Before the launch of GRACE satellite mission, possibility of obtaining GIA from GRACE and altimetry data were hypothesized (see Wahr et al., 2000, Riva et al., 2009).
- This signal separation is not easy as the quantities observed by various observation systems are related to GIA and PDSMC differently

Uncertainties in GIA:

Evaluating 13 GIA forward model solutions*





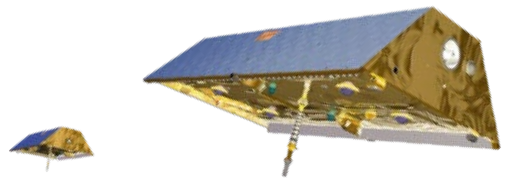


Motivation for data-driven GIA solution:

- Permanent GPS data (since ~1980)
- GRACE data since 2003

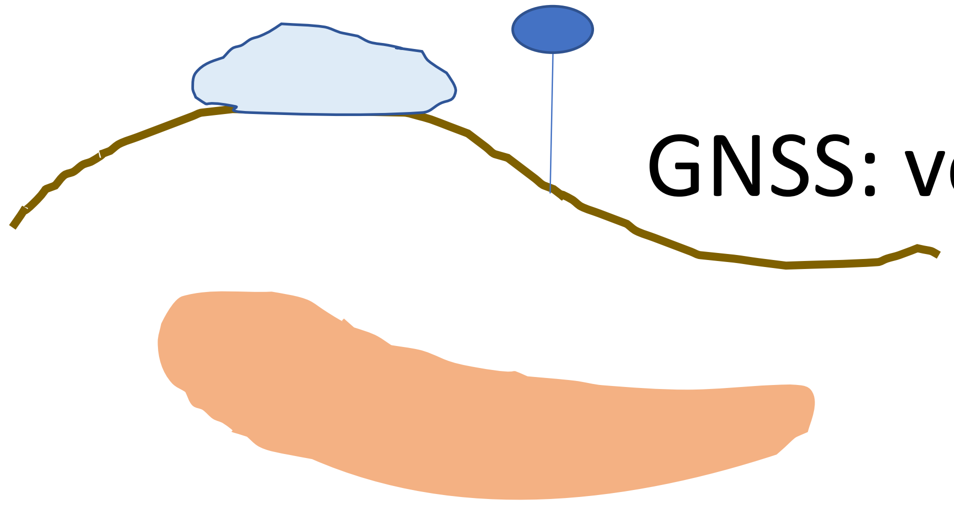
*provided by Chaoyang Zhang (Guo et al., 2012)

Observations and processes



GRACE: gravity

surface mass change



GNSS: vertical land movement

GIA from a forward model

	gravity	Vertical land motion
Positive Surface mass change	Positive anomaly	Subsidence
Negative surface mass change	Negative anomaly	Uplift
GIA uplift	Positive anomaly	uplift
GIA subsidence	Negative anomaly	subsidence

The relation between geopotential change due to surface mass change and elastic VLM is different from that between geopotential change due to GIA and VLM.

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

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

Our framework

- 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

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

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

Davis et al., 2004

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

Purcell et al., 2012

Adding equation for Δu_e and Δu_v gives us the total VLM

Our framework

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

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

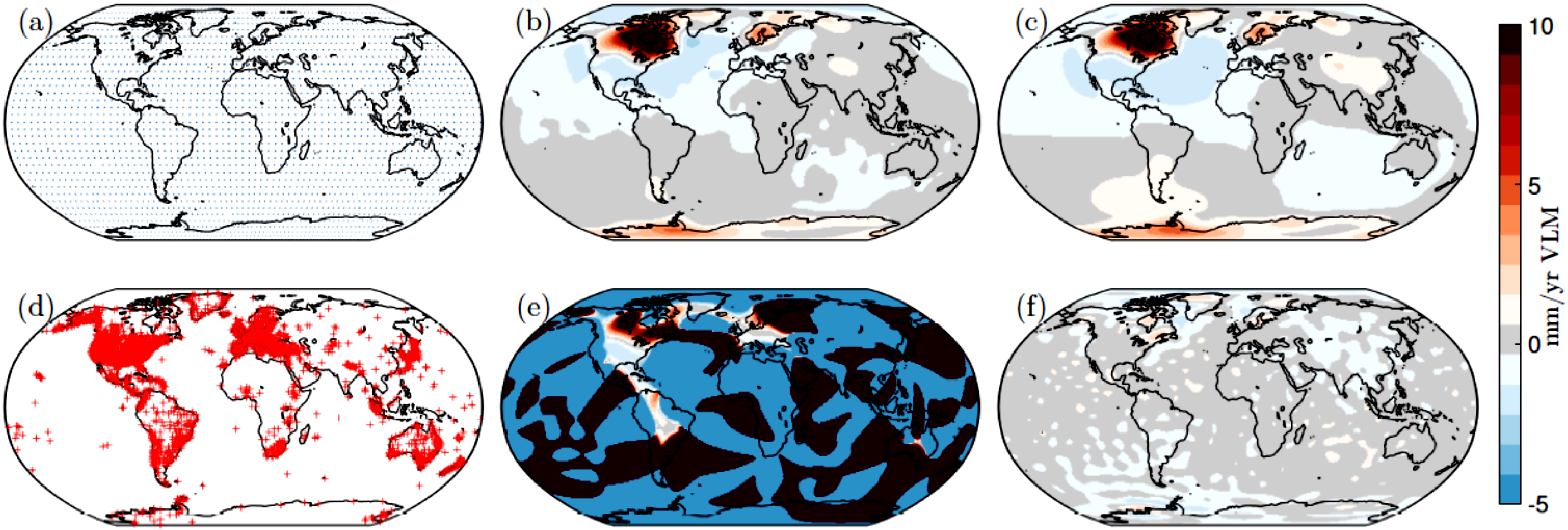
Where $\left(\Delta\dot{C}^p_{\ell m}+\Delta\dot{C}^G_{\ell m}\right)$ is available from GRACE and the right hand side is available from GPS.

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

Assumptions:

1. GPS observations observe only the sum of GIA and elastic signal due to PDSMC
   To achieve this the NGL GPS 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).

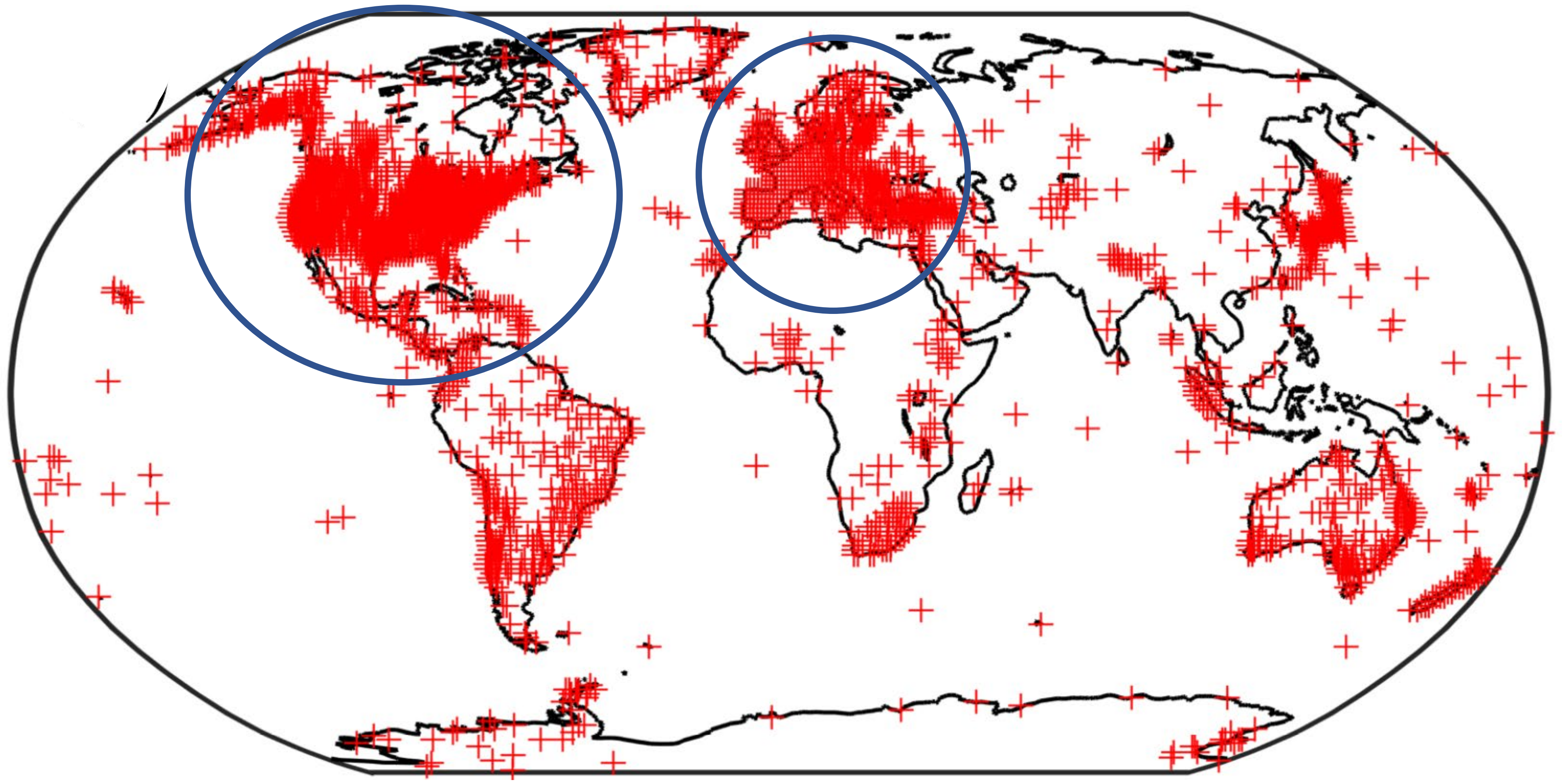
Gaps in data!

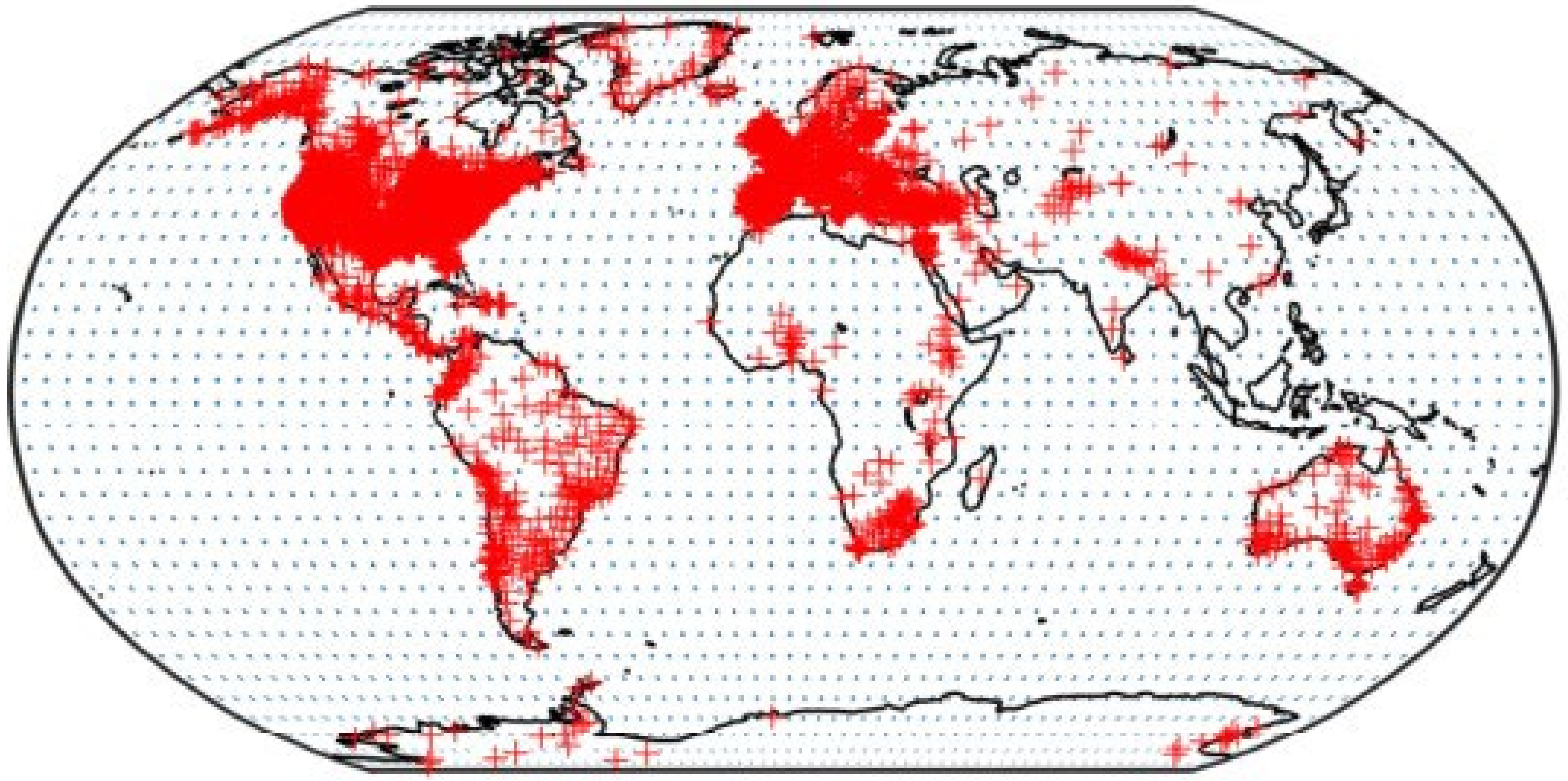
- Spatial gaps in NGL GPS network is affecting the framework and is the biggest stumbling block.

- We counter this challenge by augmenting real GPS data with synthetic data only in gaps: We check if there is a GPS station in a 5^0 X 5^0 box, if not we place a synthetic GNSS station at the centre of the 5^0 X 5^0 grid cell.

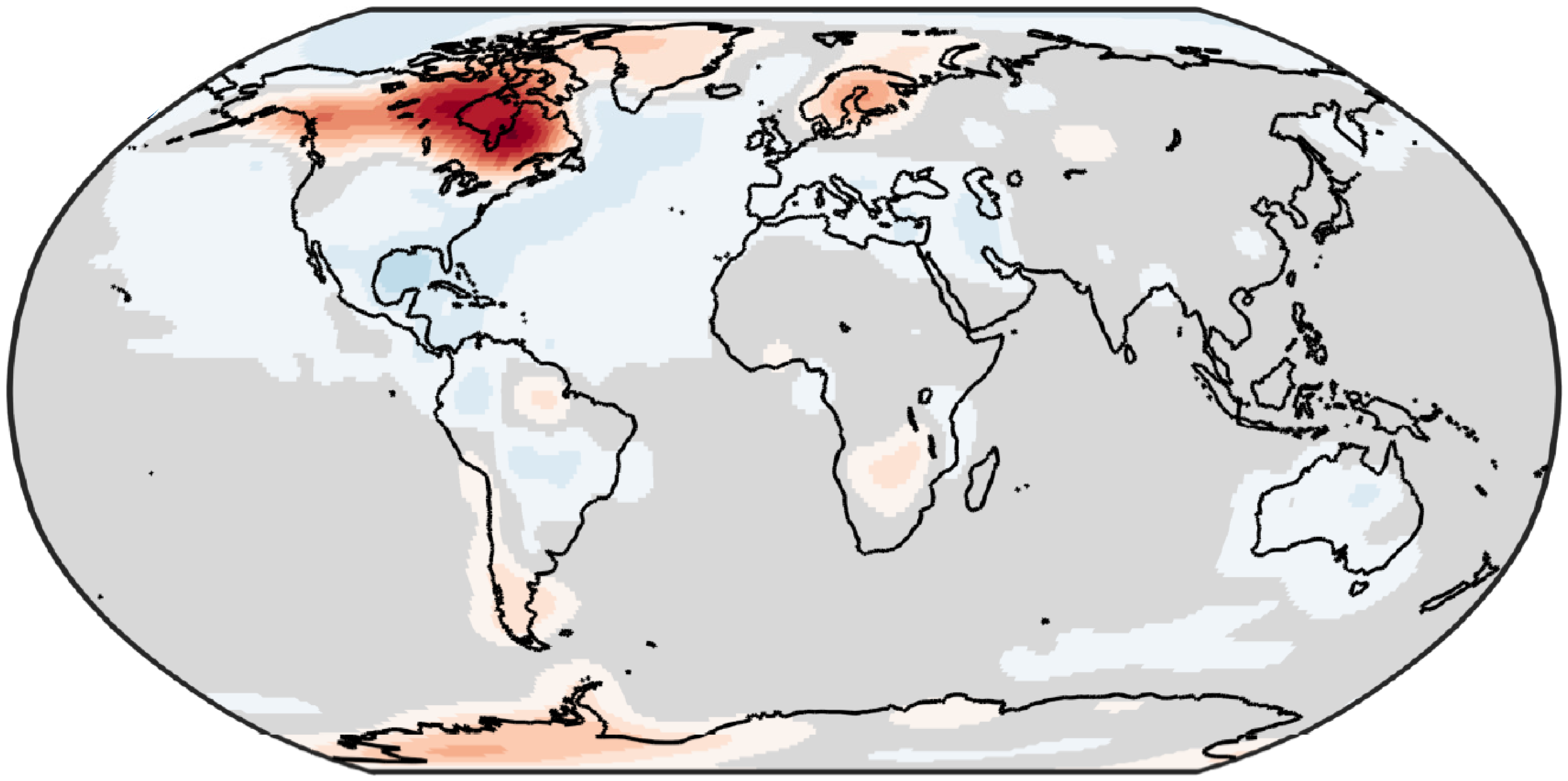
- This augmentation is equivalent to providing a prior information for locations where we do not have data.

- 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.



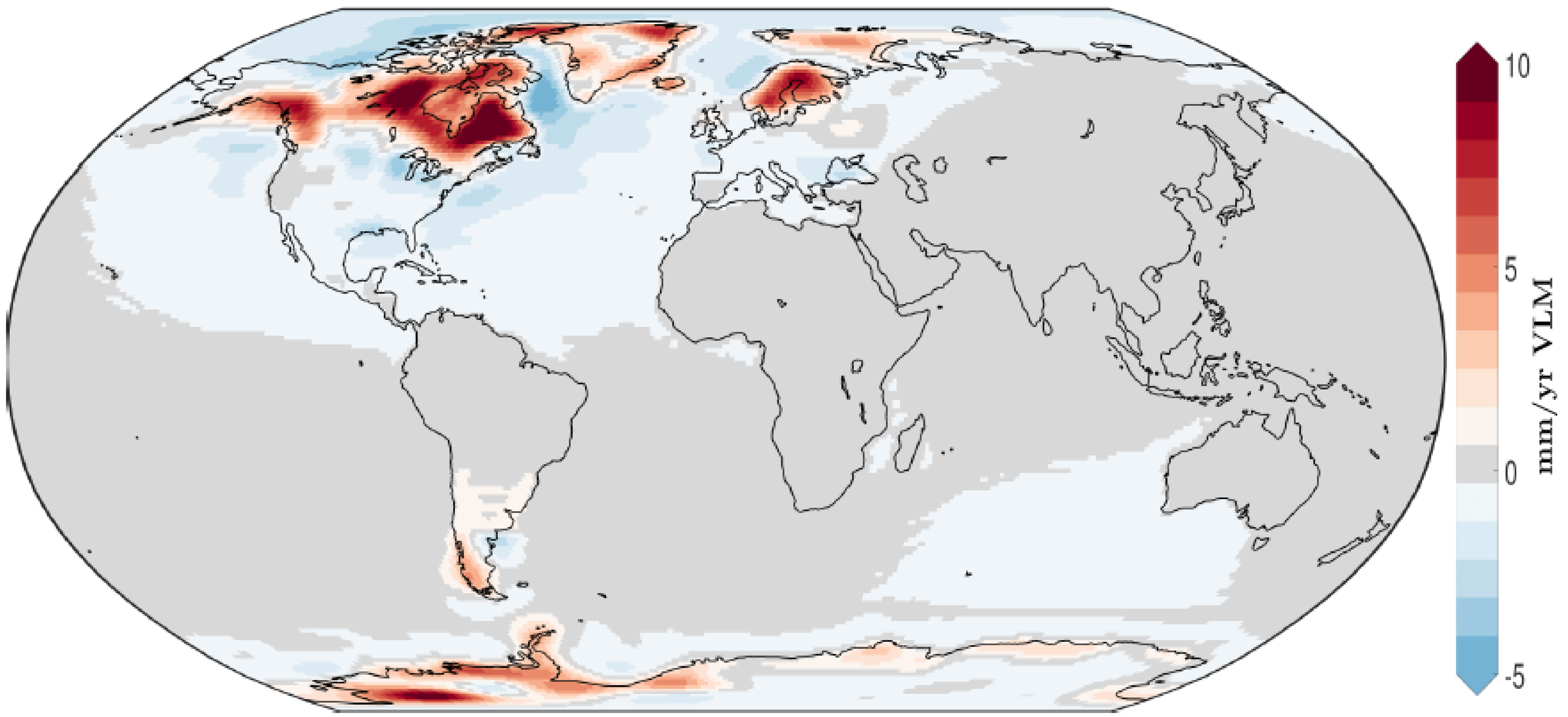


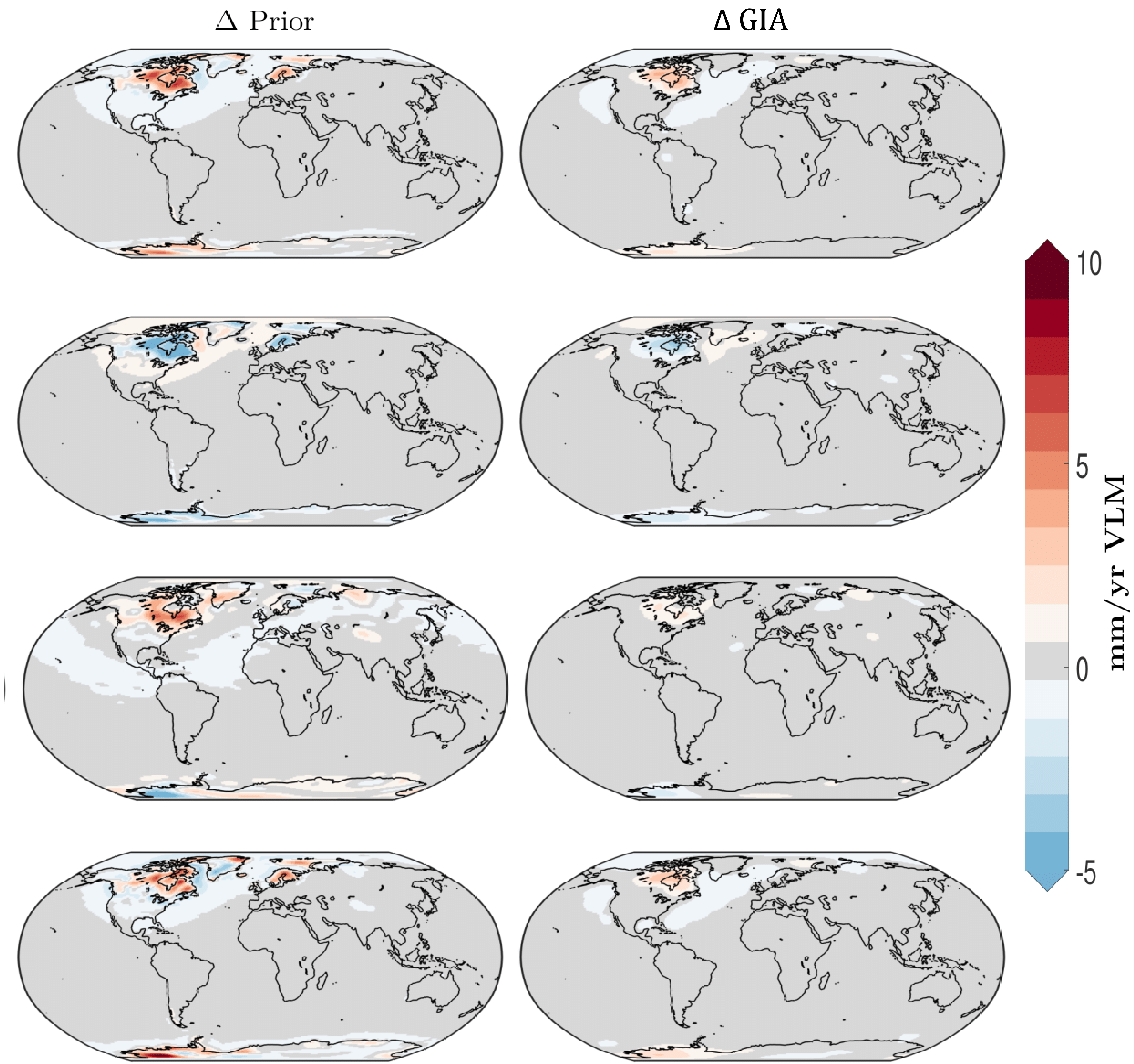
Results



- GIA solution up to degree and order 35
- Resolution is coarse and we get some signals in non-GIA regions
- Use forward modelling approach to artificially improve the resolution

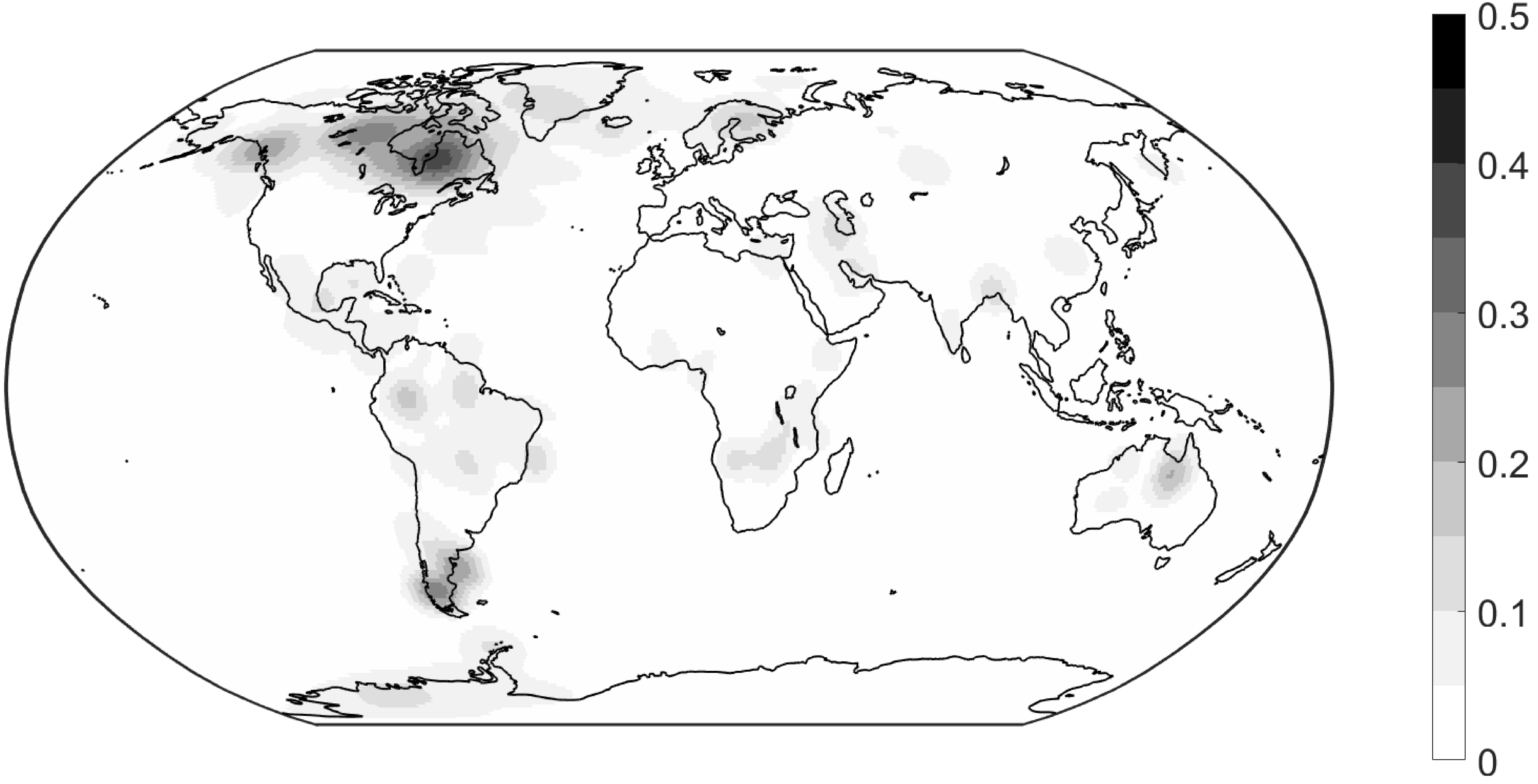
- Mask out regions with no GIA expected
- Conservation of mass is a hard constraint
- Improve the resolution to 1 degree





Sensistivity to prior

Uncertainty

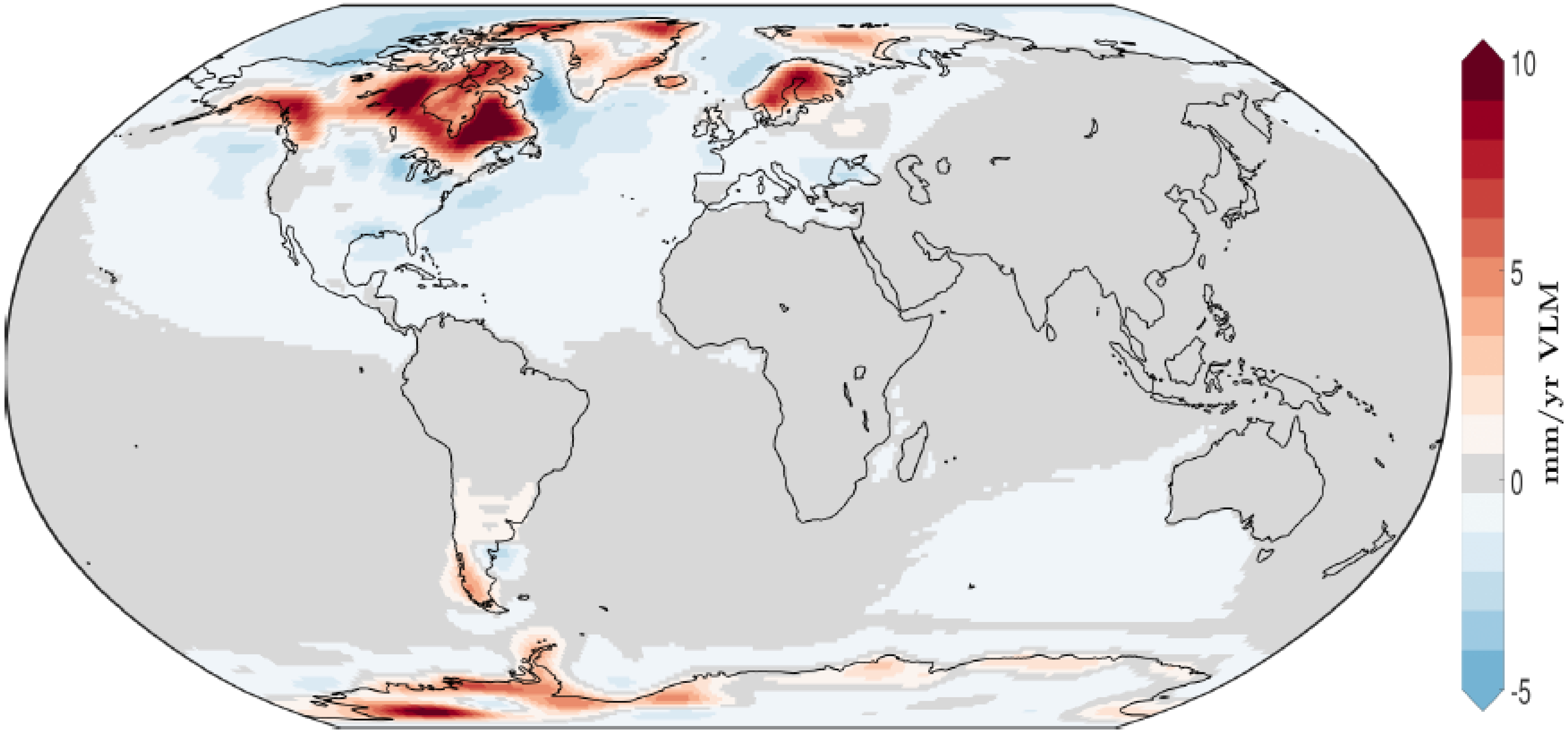


Uncertainty determined in a Monte-Carlo simulation environment, where the prior GIA models were allowed to vary between 20% of the magnitude and then the GIA outputs were obtained 100 times. The standard deviation of the GIA output is referred to as the uncertainty. Units are mm/yr.

Conclusions and Caveats

- Mathematical framework developed to separate PDSMC and GIA from GRACE and GPS data
- The method works in a synthetic closed-loop environment, and 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 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 GJI

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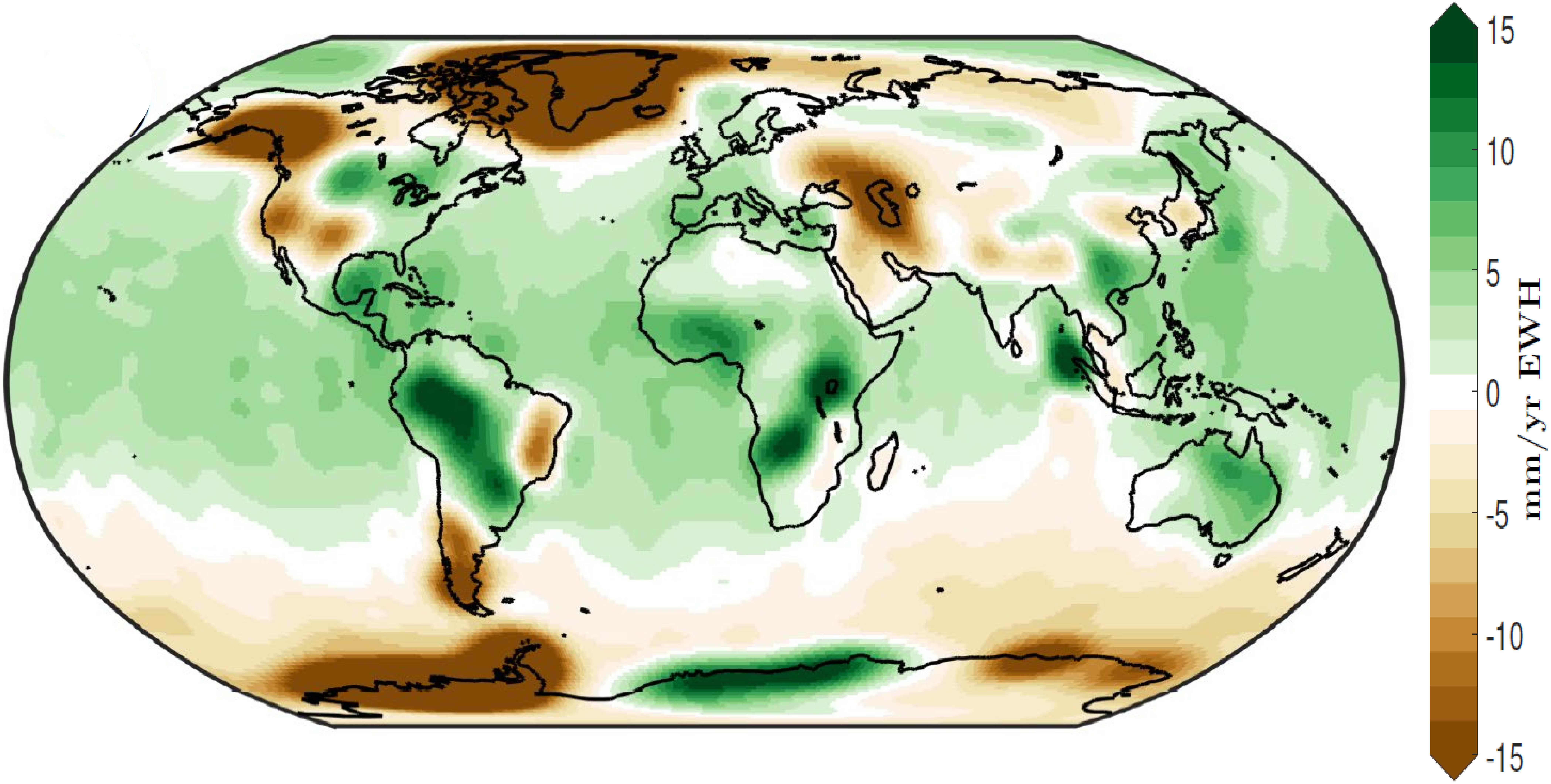
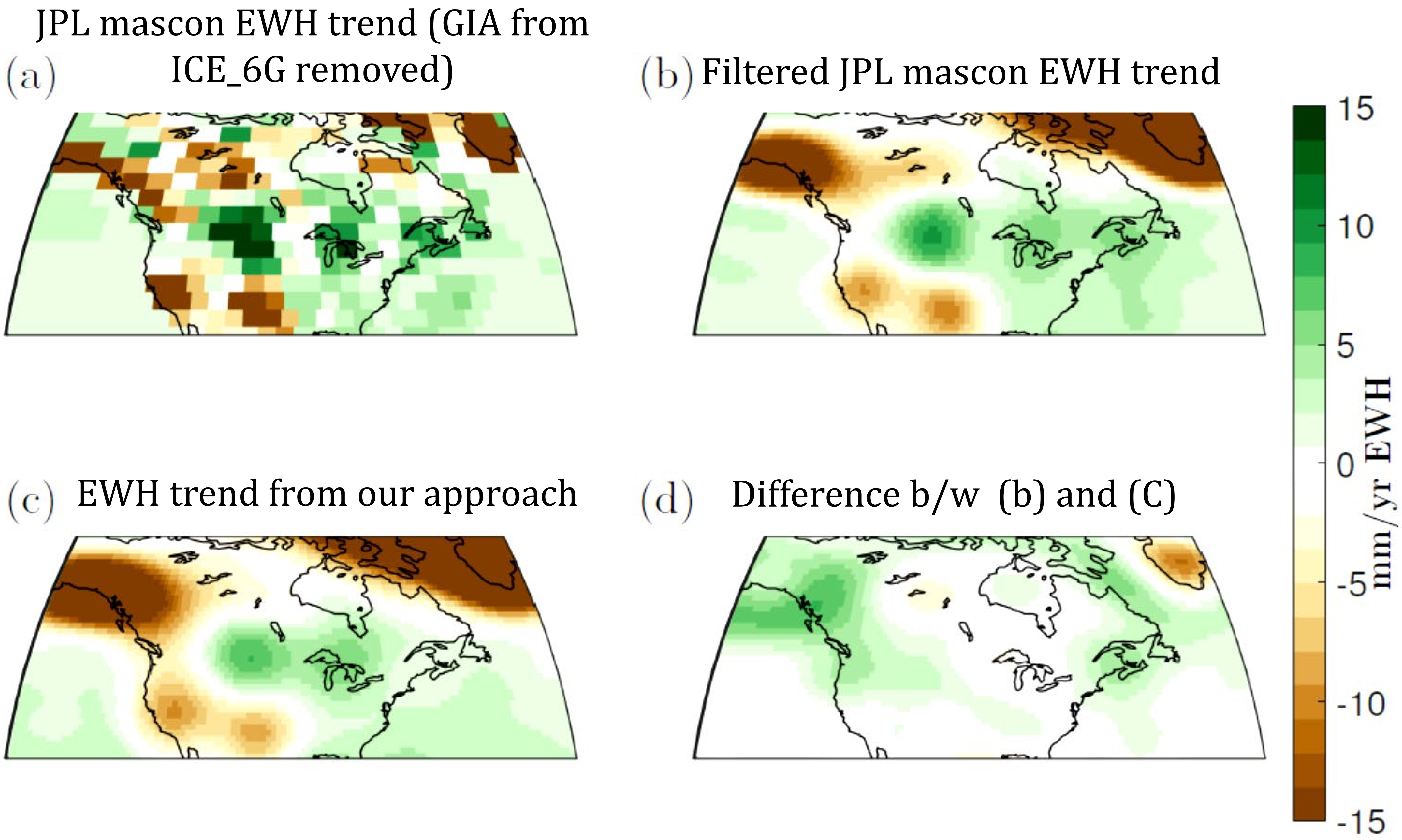
Back up slides:

EWH trend from our framework

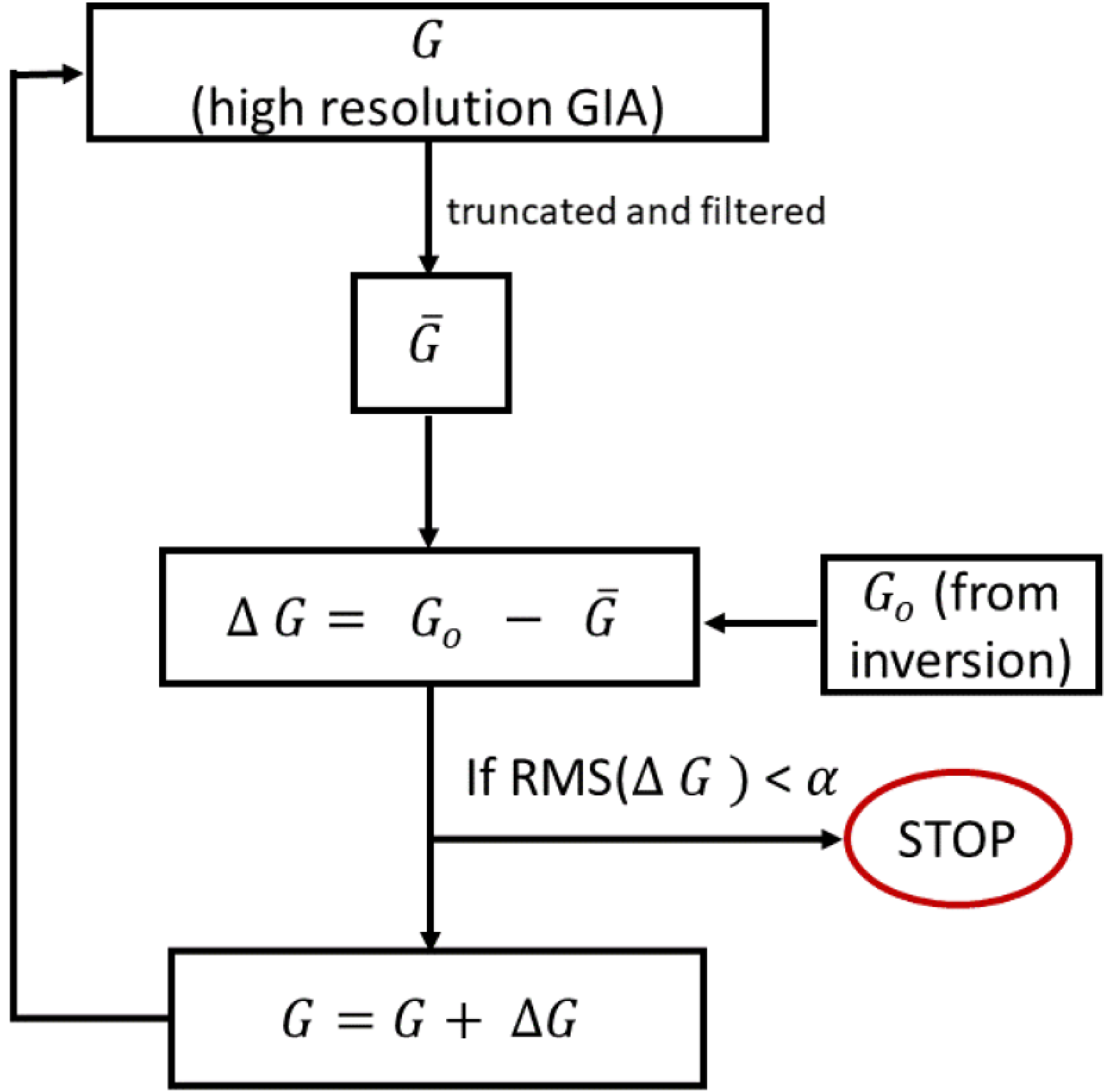


Our framework can be modified to estimate surface mass trends as well!



Comparison of our PDSMC estimates and that obtained from JPL mascons treated with ICE_6G GIA model

The Forward modelling approach by Chen et al., 2015



Signals from the present and the past: