

Glacial Isostatic Adjustment: observations, models and their uncertainties

D. Melini⁽¹⁾ & G. Spada⁽²⁾

(1) Istituto Nazionale di Geofisica e Vulcanologia, Roma

(2) Dipartimento di Fisica e Astronomia, Università di Bologna

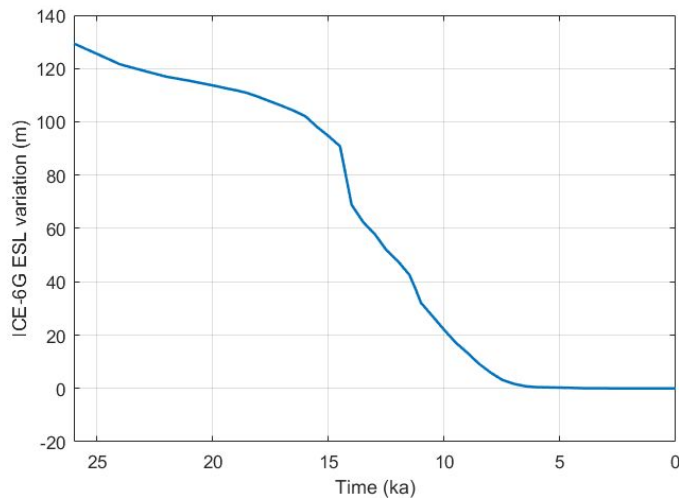
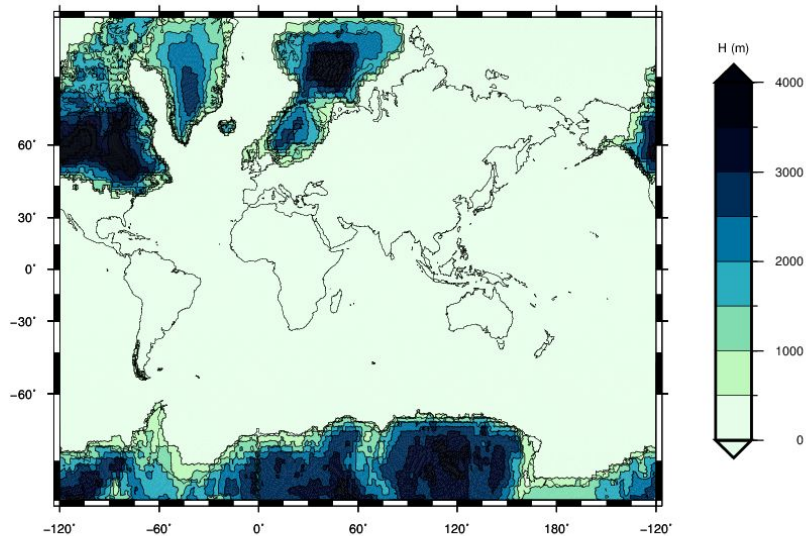
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Why studying GIA model uncertainties?

- GIA models are important for the **interpretation of a wide range of geophysical data**: sea-level rise observations, gravity field variations from satellite missions, GNSS observations, ...
- The **long-term trend of relative sea-level** at tide-gauges is significantly affected by GIA, which contaminates the sea-level records at all latitudes, hence affecting estimates of global mean sea-level rise.
- Due to their widespread use in the geophysical and climate change community, a rigorous assessment of the intrinsic uncertainties of GIA models is needed as a requisite for the **closure of contemporary sea-level budget**.
- With the aim of **improving existing heuristic estimates** (e.g. the “ $\pm 20\%$ rule”), here we study of GIA modeling uncertainties associated to various quantities of interest in geodetic and geophysical investigations.

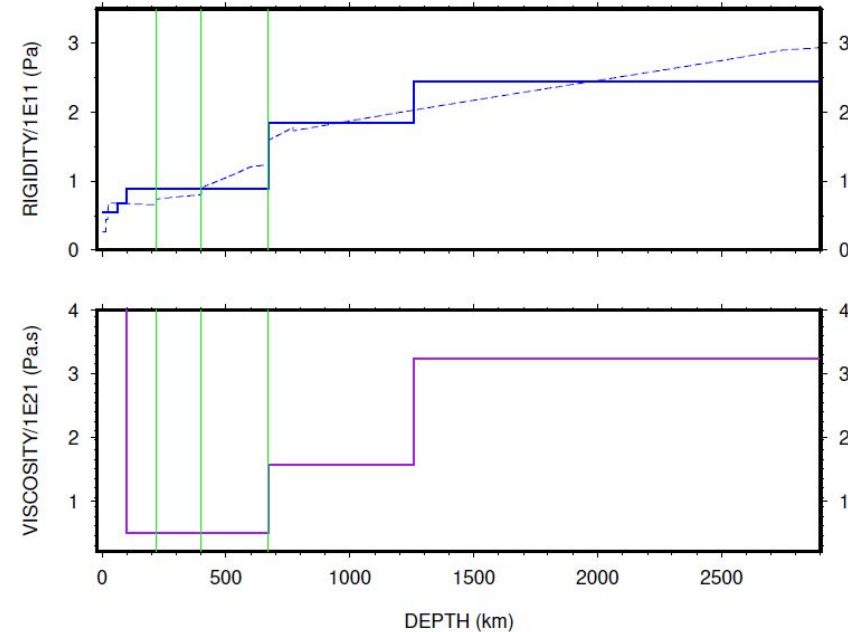
Ingredients of a GIA model

1) Spatio-temporal evolution of ice sheets



&

2) Rheological model



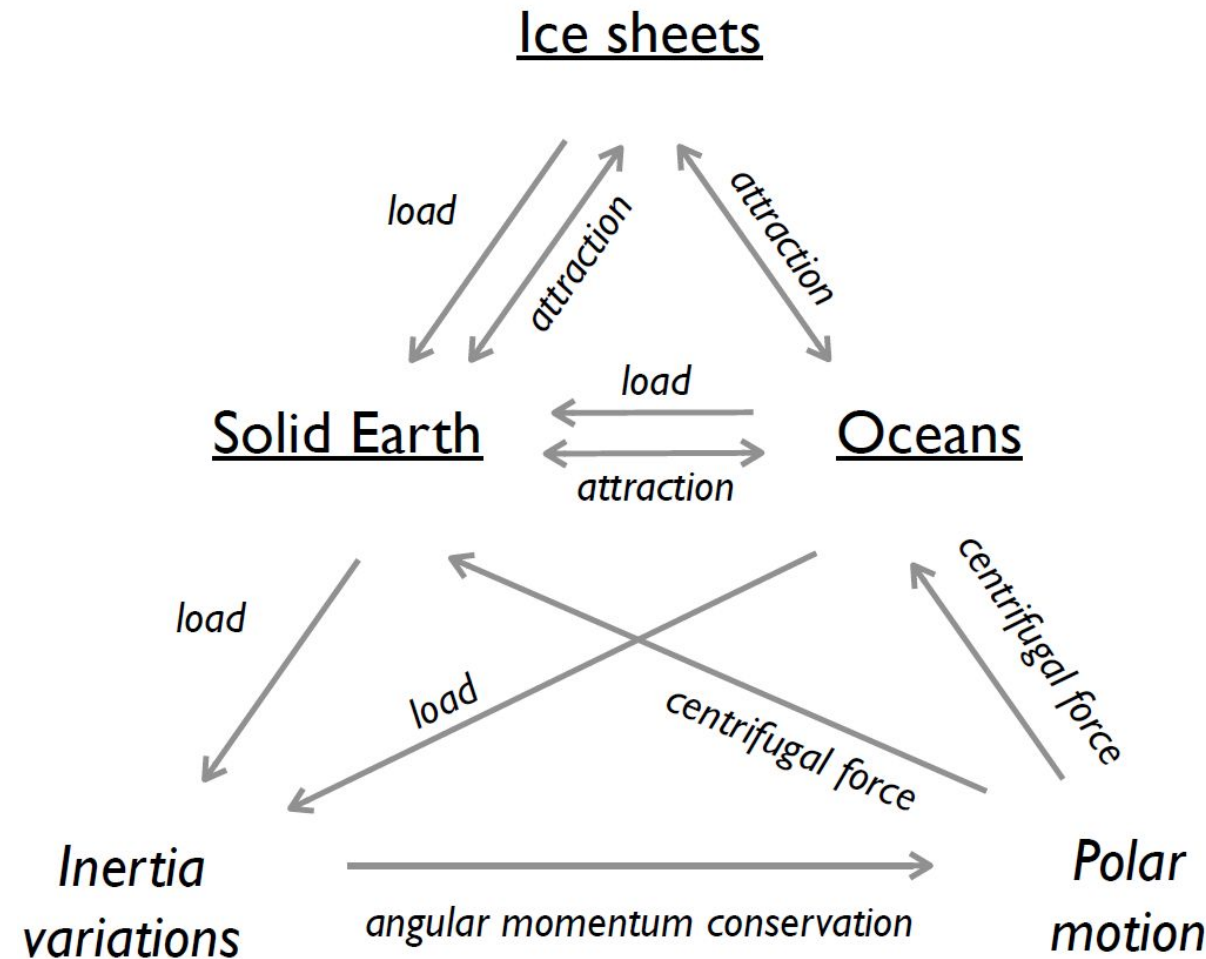
Constraints: Records of past Relative Sea Level (RSL)

Predictions: Synthetic RSL curves, present-day geodetic “fingerprints”, GIA corrections for secular SLR at TGs, Paleo-topography maps, ...

Solving a GIA model: the “Sea Level Equation”

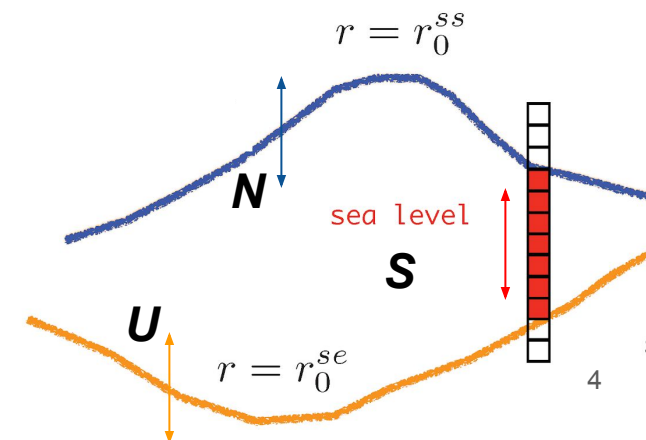
The Sea Level Equation (SLE) describes the interactions within the **Solid Earth + Oceans + Ice sheets** system.

Except for the simplest cases, the SLE must be solved numerically adopting an iterative scheme.



Adapted from Clark & others

$$S = N - U$$



Uncertainties in a GIA model: where do they come from?

Few efforts have been devoted to the systematic study of possible sources of model uncertainties. We propose their classification into two broad (and partly overlapping) categories:

T1, “input uncertainties”

- Imperfect knowledge of the Earth interior (e.g. viscosity & rheological profile)
- Uncertainty on the margins of the ice complexes and on the deglaciation history

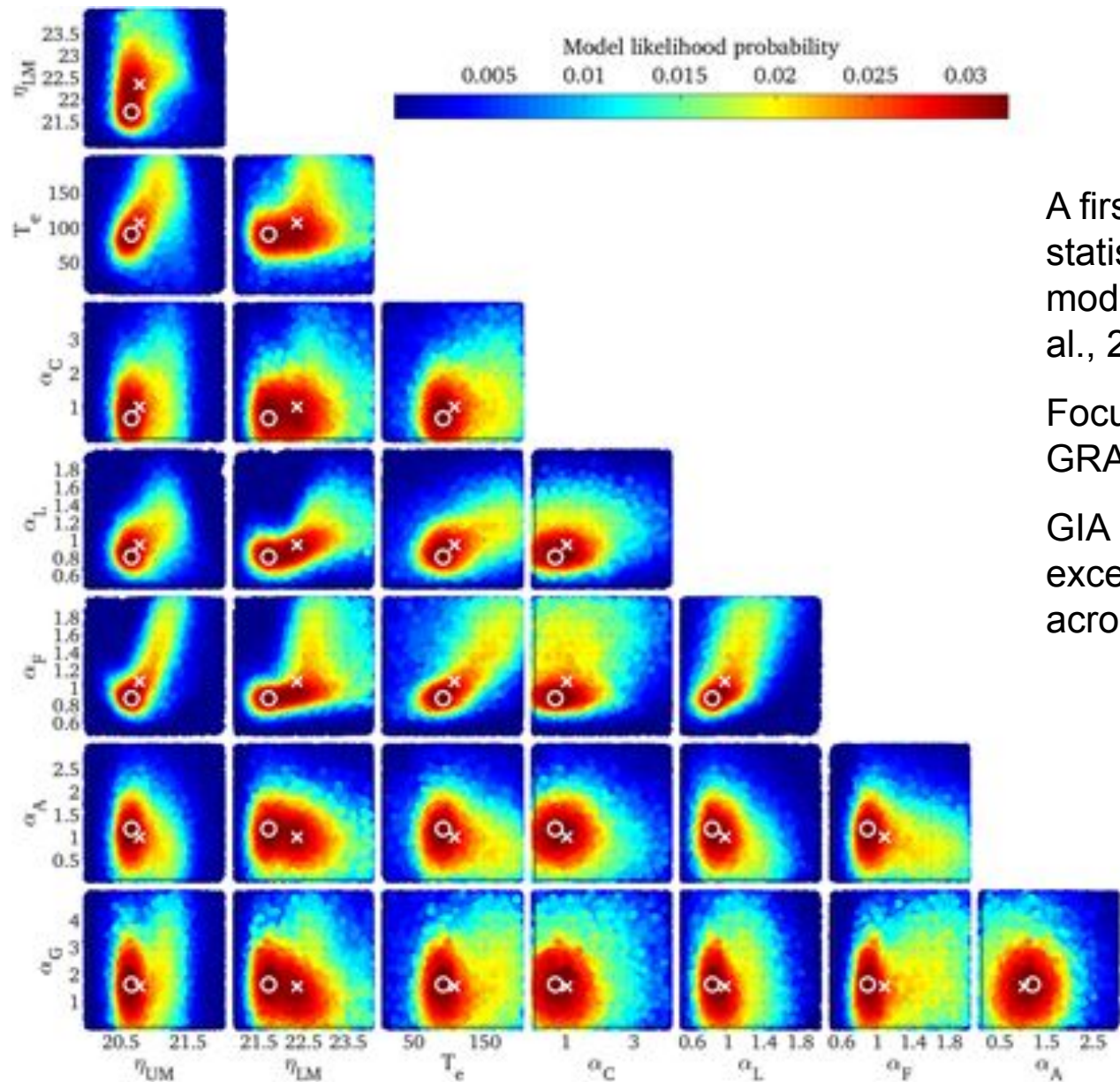
T2, “structural uncertainties”

- Different numerical implementations of the SLE (no community-agreed set of gravitationally and topographically self-consistent solutions)
- Methodological discordances between different research groups
- Different observation sets used to constrain the model

Evaluating “input uncertainties” (T1)

1. We focus on the **ICE-3G(VM1)** GIA model (outdated, but computationally simple)
2. We generate **500.000 random variations** of ICE-3G by varying:
 - The distribution of ice volumes across Northern Europe, North America and Antarctica ice complexes, keeping the total ESL curve unaltered
 - The lithospheric thickness
 - The mantle viscosity
3. For each model in the ensemble, we solve the SLE (through a compute-optimized variant of the SELEN code) and compute synthetic RSL curves at the 191 sites of the Tushingham and Peltier database
4. We select ensemble items for which the misfit is statistically equivalent (at the 95% CL) with the “nominal” ICE-3G model (**23,709 models - 4.6% of the initial sample**).
5. We compute model uncertainties as statistics over the sub-ensemble of “ICE-3G equivalent” models

Evaluating “input uncertainties” (T1)



A first attempt to a rigorous statistics characterization of GIA model uncertainties is in Caron et al., 2018.

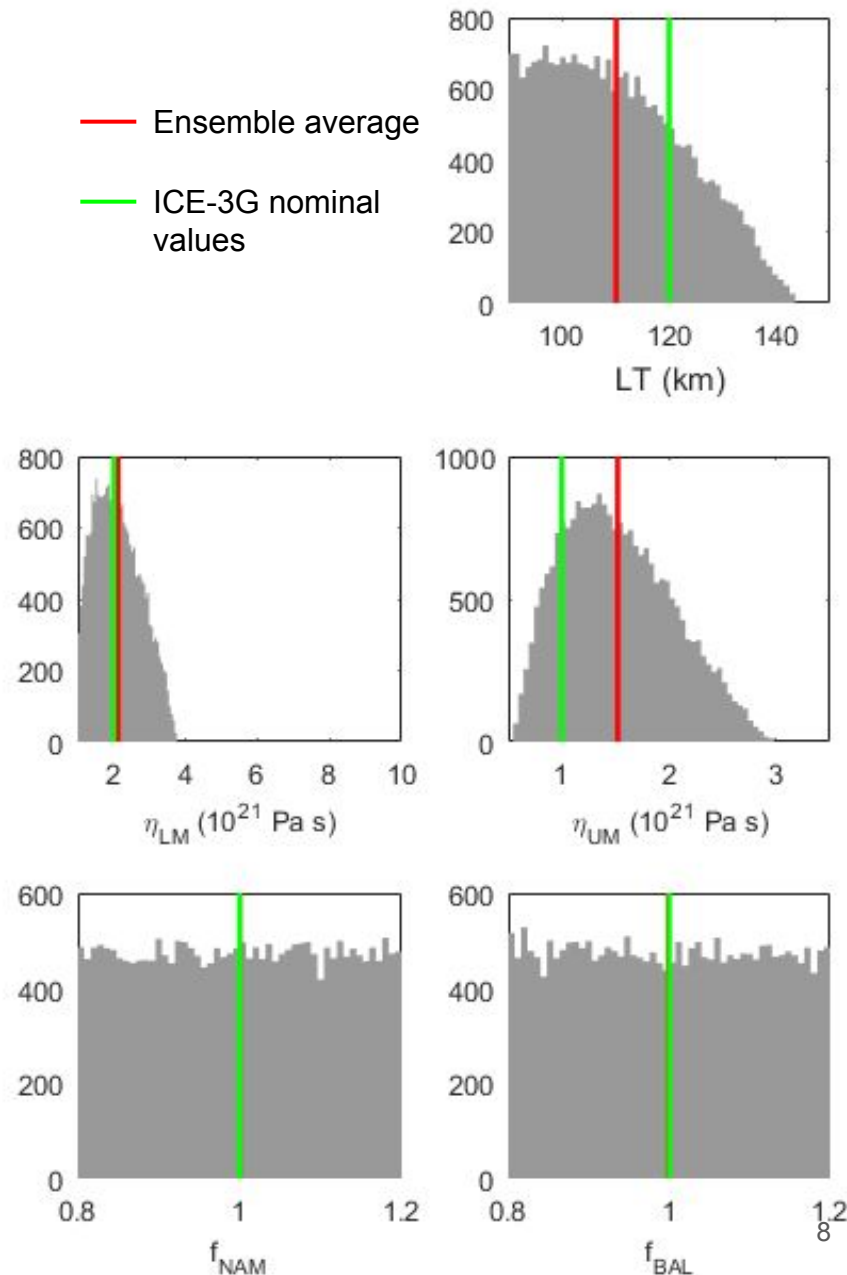
Focus is on GIA corrections to GRACE surface mass trends.

GIA uncertainties are found to exceed those in GRACE data across the polar regions.

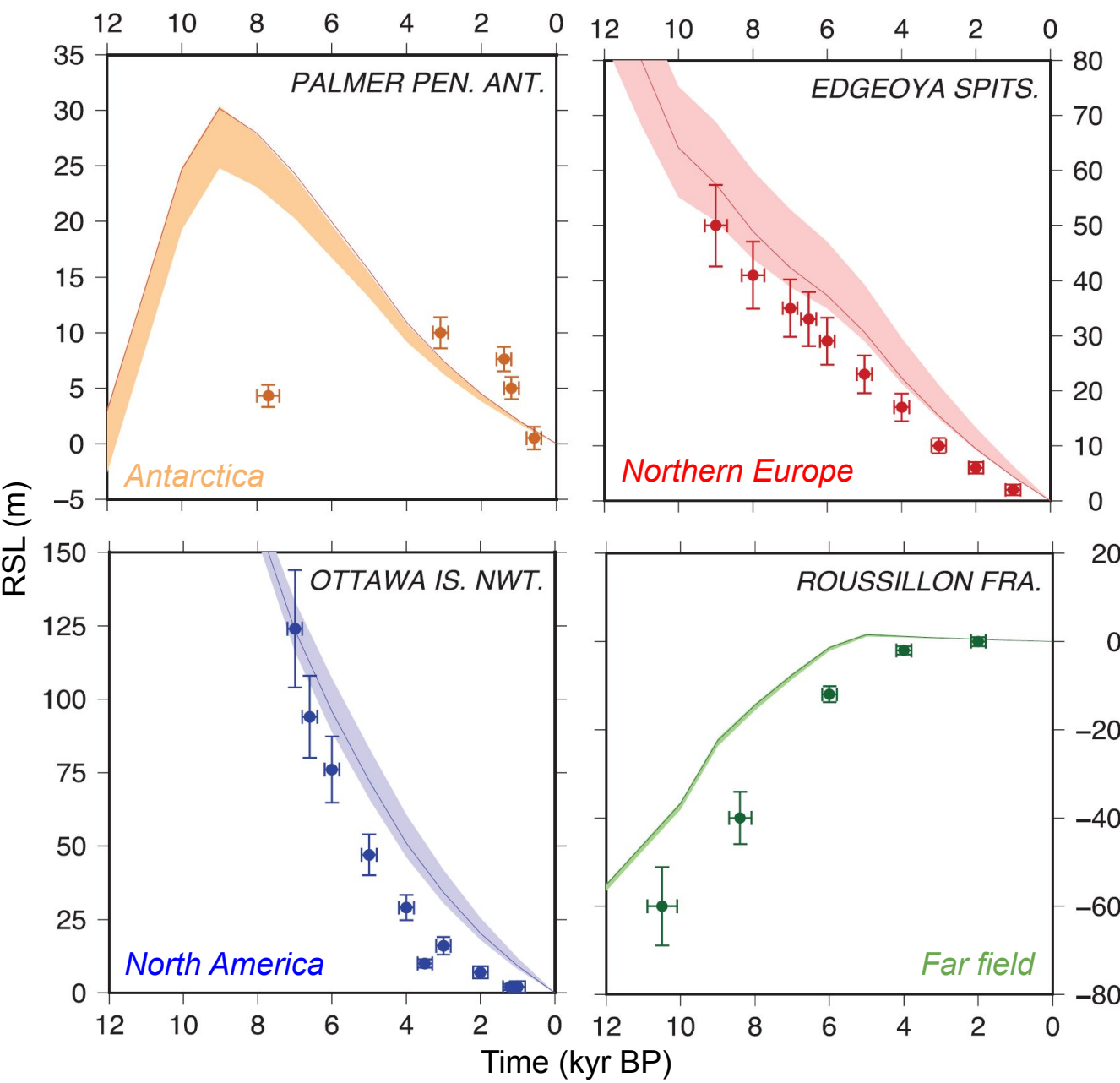
From Caron et al, GRL, 2018

Evaluating “input uncertainties” (T1)

	Ensemble range	Nominal value for ICE-3G (VM1)	Average for “ICE-3G equivalent” models
Lithospheric thickness (km)	90-150	120	110 ± 13
UM viscosity (10^{21} Pa s)	0.5-3.5	1	1.5 ± 0.5
LM viscosity (10^{21} Pa s)	1-20	2	2.1 ± 0.6
Scale factor for Laurentide volume	0.8-1.2	1.0	1.0 ± 0.1
Scale factor for Fennoscandia volume	0.8-1.2	1.0	1.0 ± 0.1



T1 uncertainties on RSL in the past



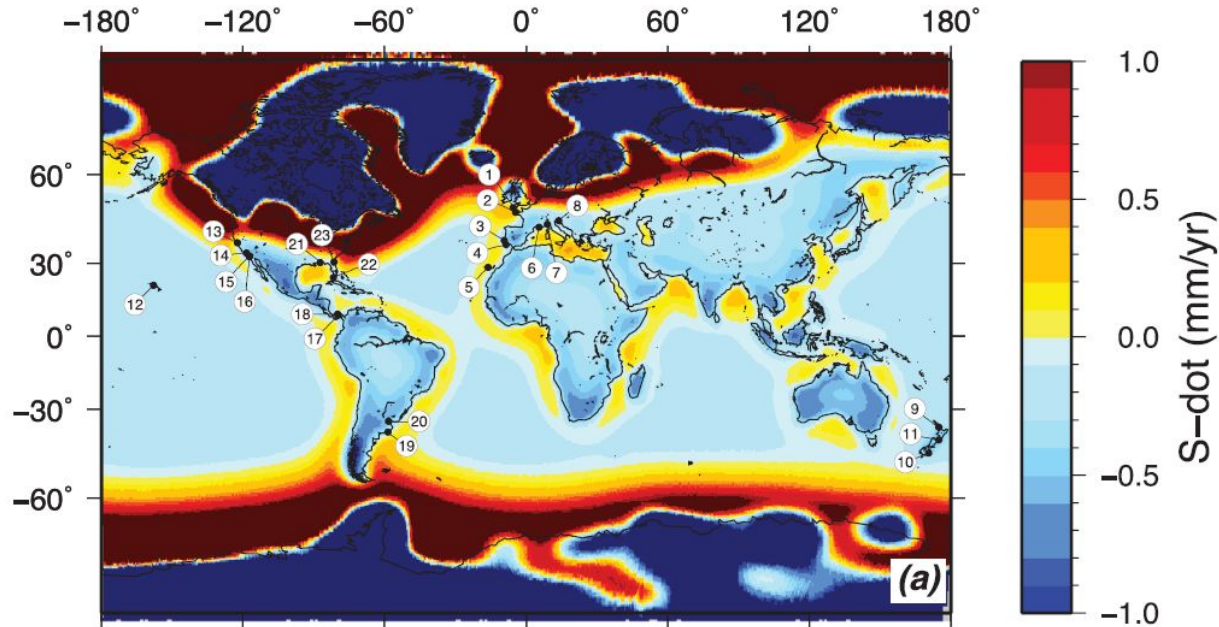
Synthetic RSL curves vs T&P1991 data at four sites in the T&P database.

GIA uncertainties are significant near the former ice sheets, sometimes exceeding the data uncertainty

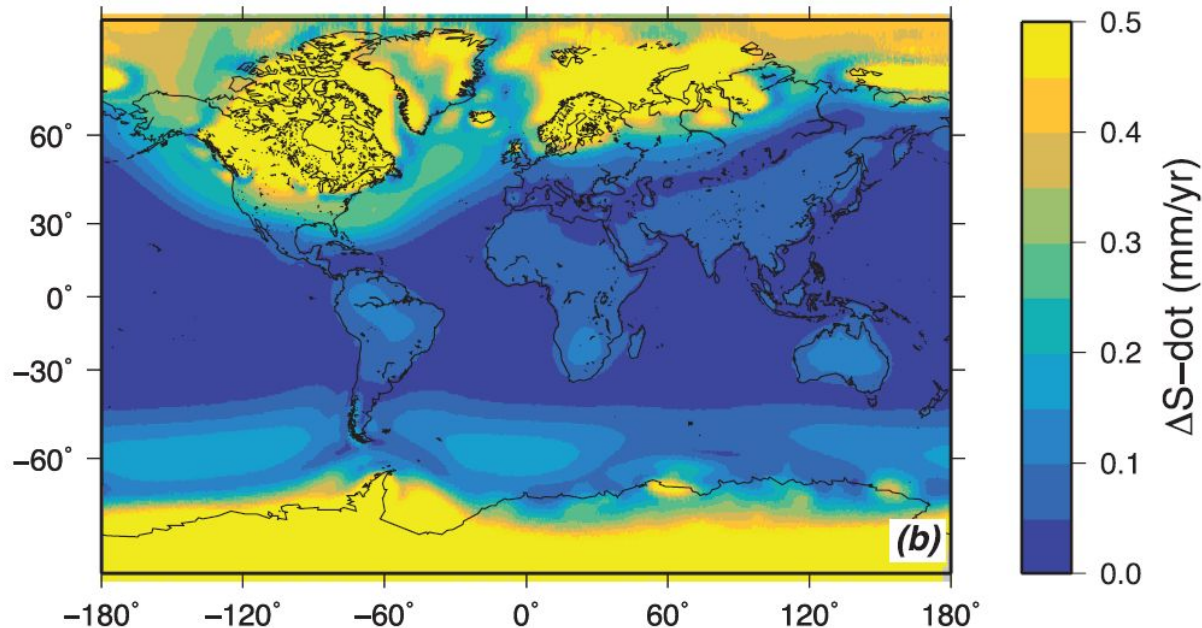
Maximum GIA relative uncertainty is obtained at **7kyr BP**

20% of the GIA RSL predictions for the T&P1991 database have a relative uncertainty **> 30%**

T1 uncertainties on geodetic “fingerprints”



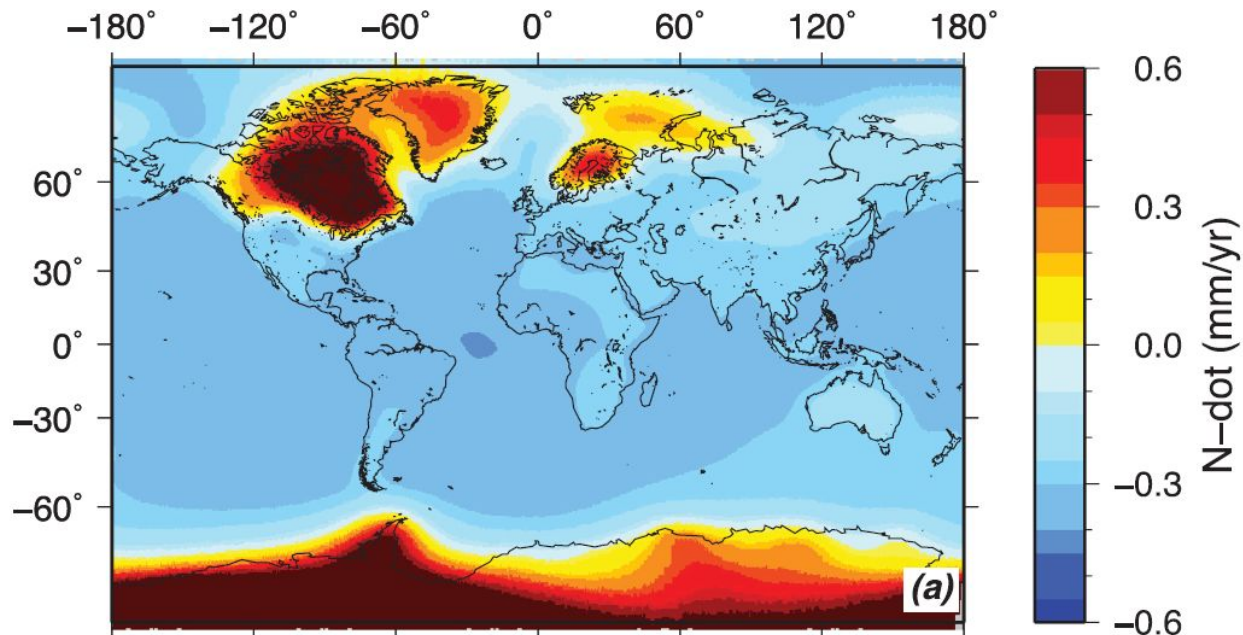
Present-day dS/dt “fingerprints” and their $1-\sigma$ $T1$ uncertainty



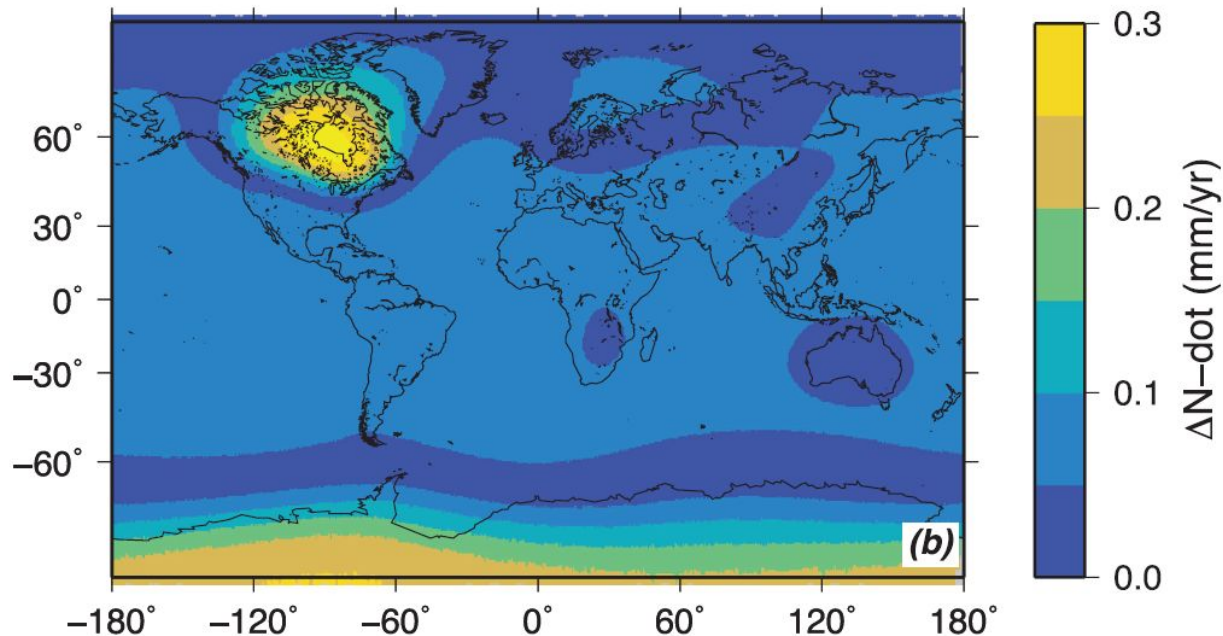
Minimum uncertainties are found in the **equatorial region** (**<0.1 mm/yr**)

Maximum uncertainties are found **across the formerly glaciated region** (up to **2.2 mm/yr**).

T1 uncertainties on geodetic “fingerprints”



Present-day dN/dt “fingerprints” and their $1-\sigma$ $T1$ uncertainty

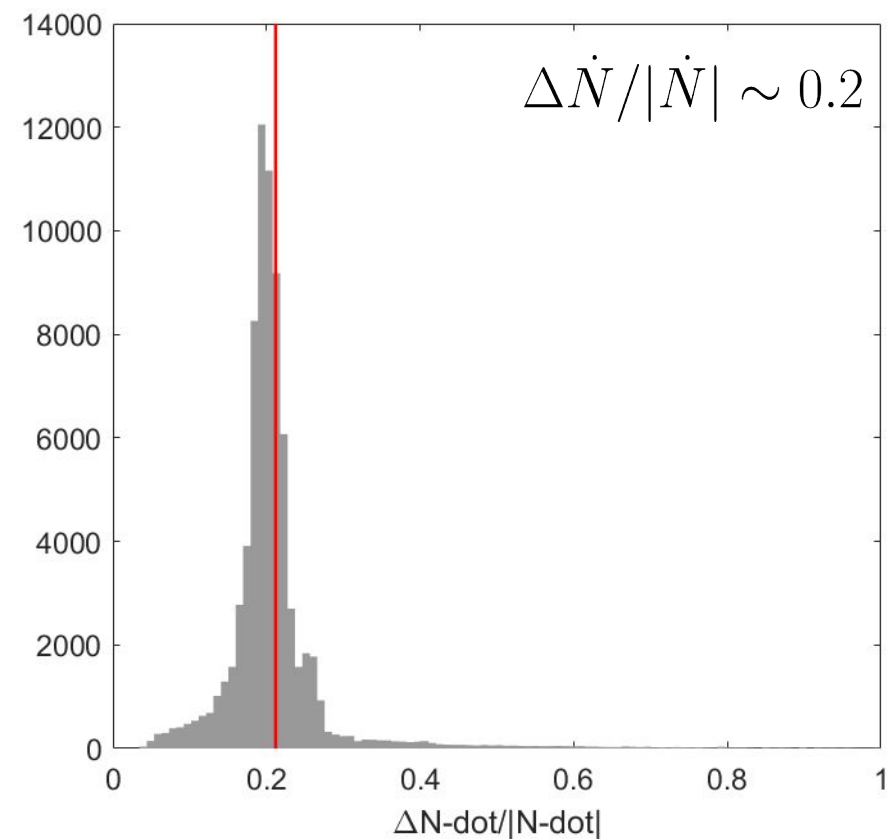
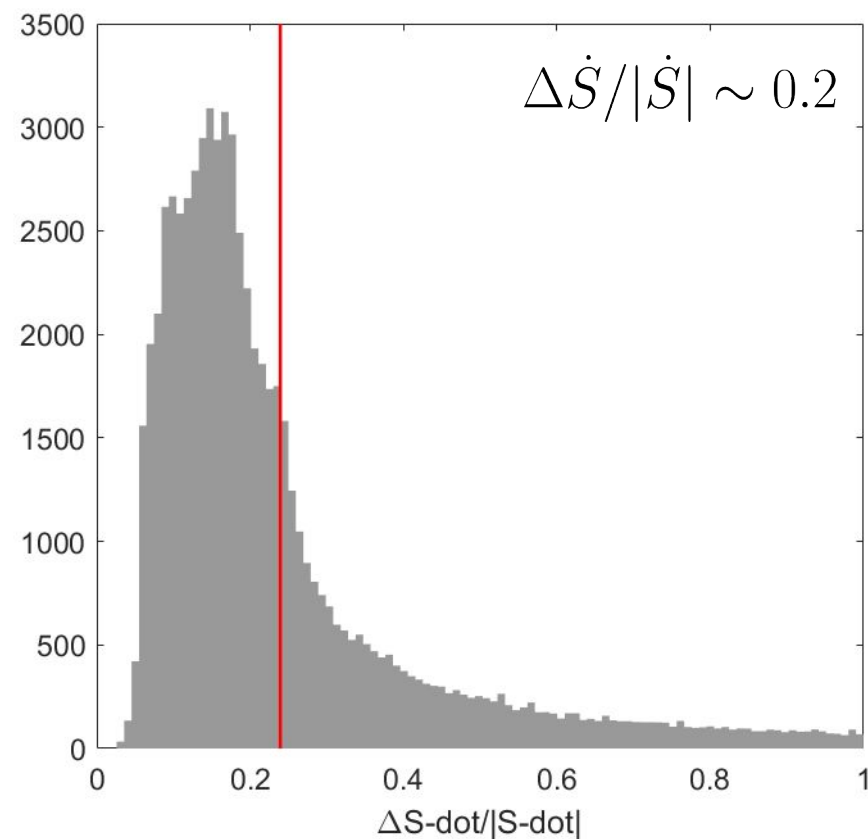


The average of dN/dt over the ocean surface is

$$\langle \dot{N} \rangle = (-0.30 \pm 0.06) \text{ mm/yr}$$

Despite dN/dt being small compared to SLR observations in the altimetry era (3.5 mm/yr), its relative uncertainty is significant (20%)

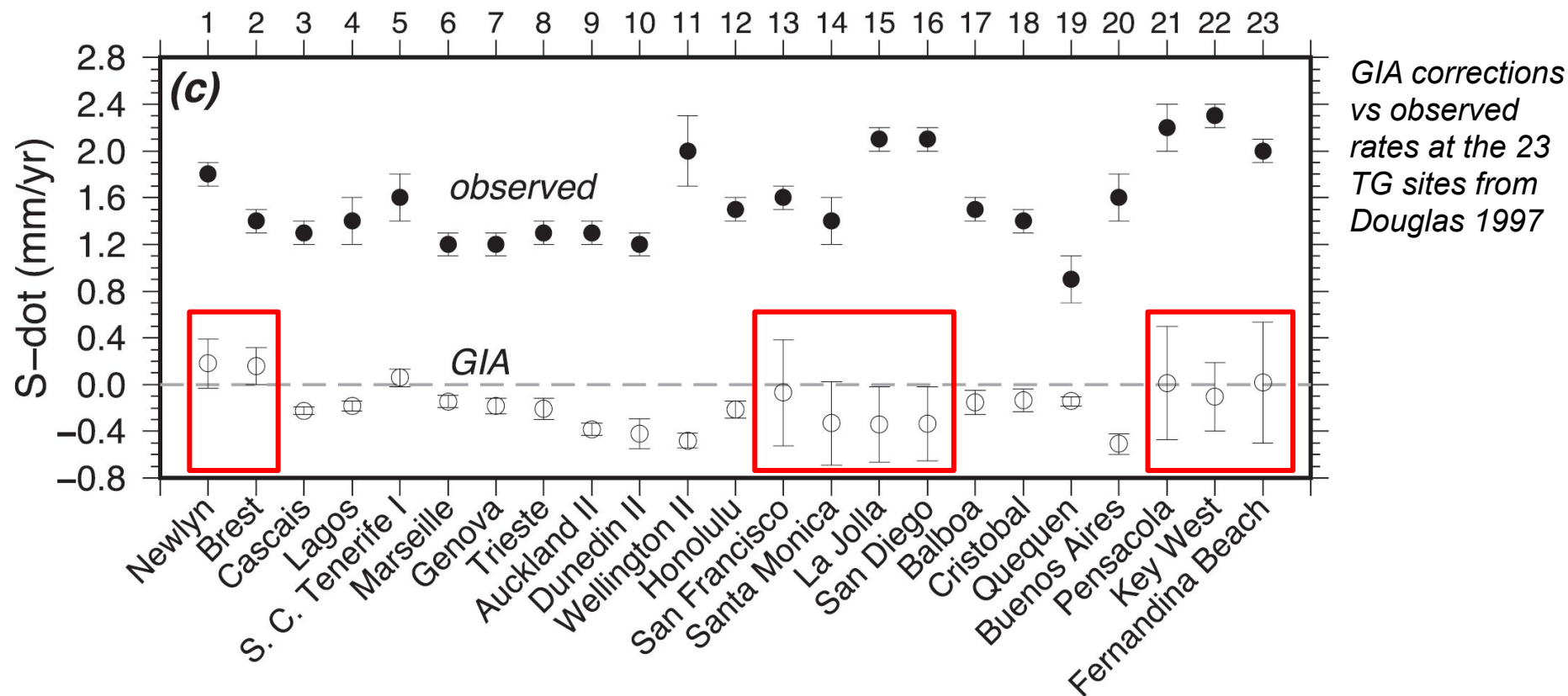
T1 uncertainties on geodetic “fingerprints”



Relative T1 uncertainties on \dot{S} and \dot{N} are about 20% on average, consistently with the $\pm 20\%$ heuristic rule proposed in the context of GRACE.

But at 25% of the Earth surface, relative \dot{S} T1 uncertainties exceed 40%

T1 uncertainties on secular SLR at tide gauges



Uncertainties on observed SLR at TGs often exceed GIA uncertainties, **except at some sites**.

Despite their importance at specific locations, T1 uncertainties on GIA corrections **can be neglected** (at the 0.1 mm/yr level) to estimate the GMSLR uncertainty.

$$\mu = (1.58 \pm 0.38) \text{ mm/yr}$$

$$\gamma = (-0.18 \pm 0.19) \text{ mm/yr}$$

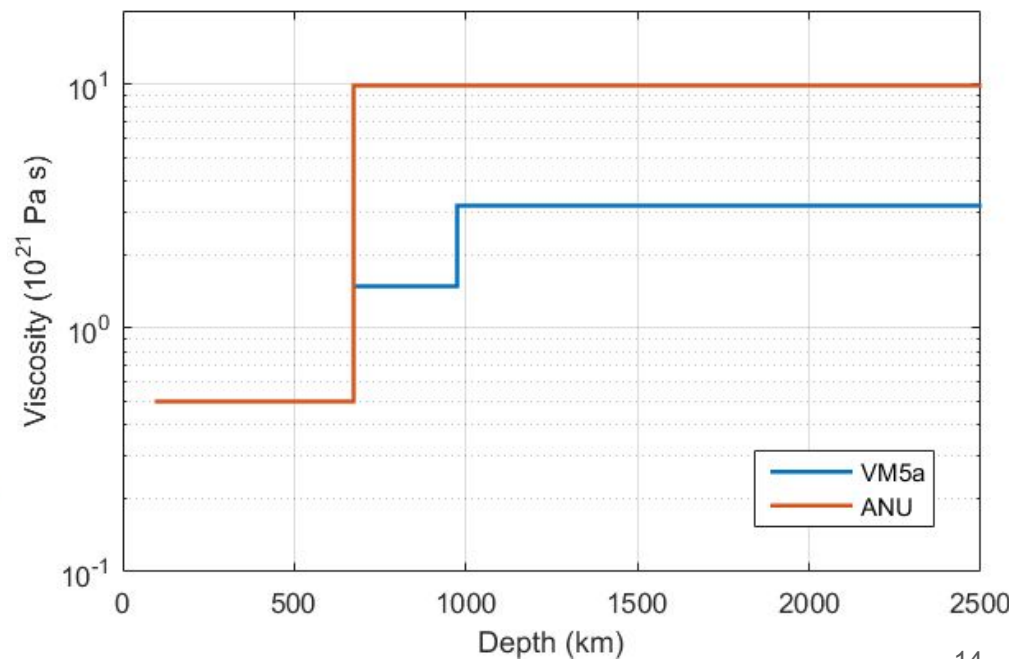
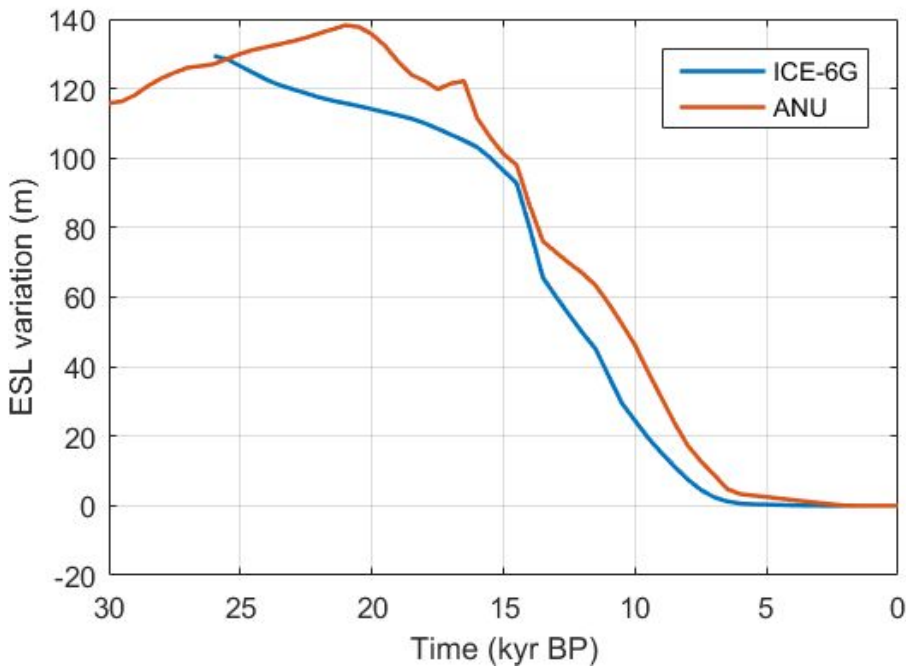
$$\rho = (\mu - \gamma) = (1.8 \pm 0.4) \text{ mm/yr}$$

Evaluating “structural uncertainties” (T2)

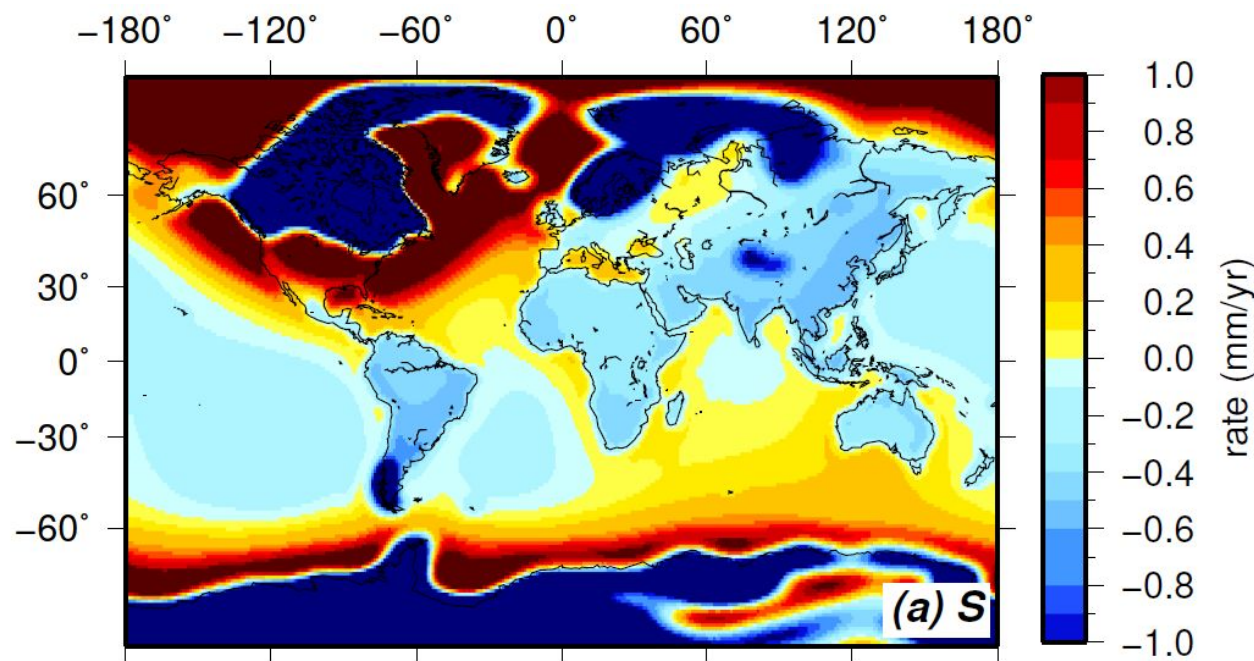
Along the lines of the IPCC AR5, we evaluate T2 uncertainties through a “mini-ensemble” approach.

Our mini-ensemble is composed by the only two testable state-of-the-art GIA models: **ICE-6G_C (VM5a)** from Peltier et al., 2005 and the GIA model by Kurt Lambeck & collaborators (**ANU**).

The mini-ensemble standard deviation is, by definition, $\sigma = |I6G - ANU|/\sqrt{2}$

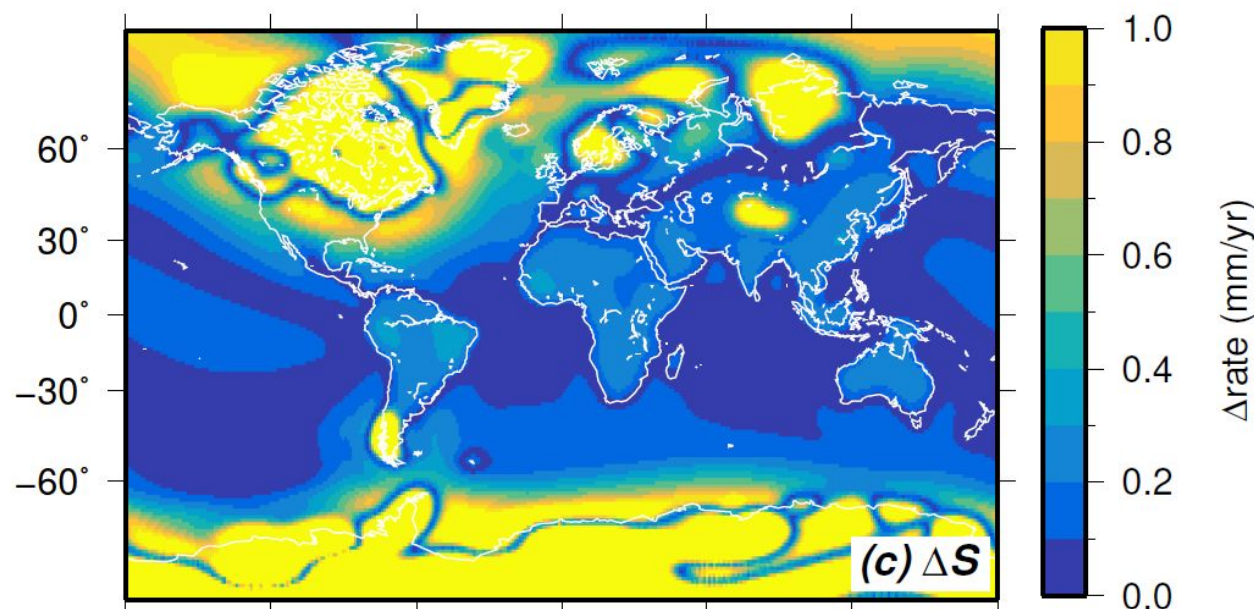


T2 uncertainties on geodetic “fingerprints”



Present-day dS/dt “fingerprints” and their $1-\sigma$ $T2$ uncertainty

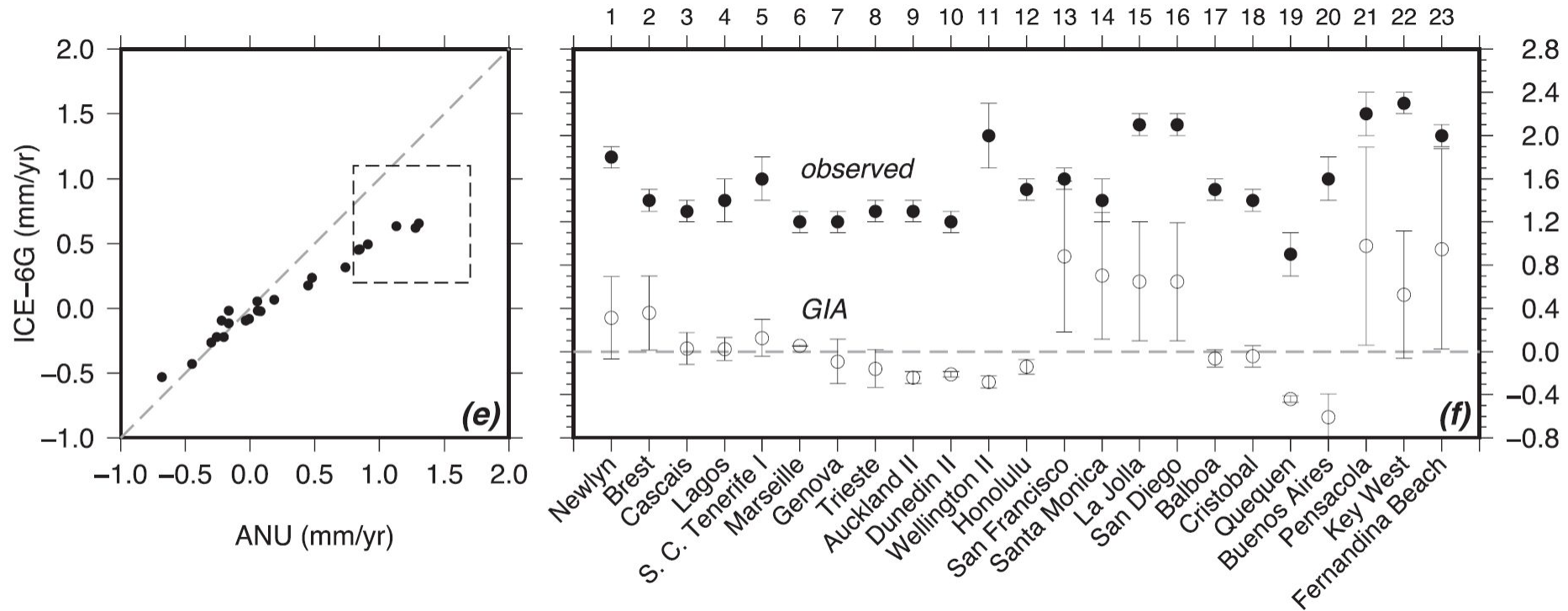
As for T1, in the equatorial region uncertainties are minimum (**<0.1 mm/yr**)



Across formerly glaciated regions, peak uncertainties largely exceed those found for T1 (**9.6 mm/yr for $\Delta S\text{-dot}$ and 0.8 mm/yr for $\Delta N\text{-dot}$**).

Consistently with T1, we find **$\langle \Delta N\text{-dot} \rangle = (-0.3 \pm 0.1)$ mm/yr**

T2 uncertainties on secular SLR at tide gauges



The two elements of the mini-ensemble (ICE-6G and ANU) give consistent predictions across the D97 tide-gauge sites, except along a series of TG sites in North America.

T2 uncertainties on GIA TG corrections are significantly larger than T1 (up to 40-60% at some sites)

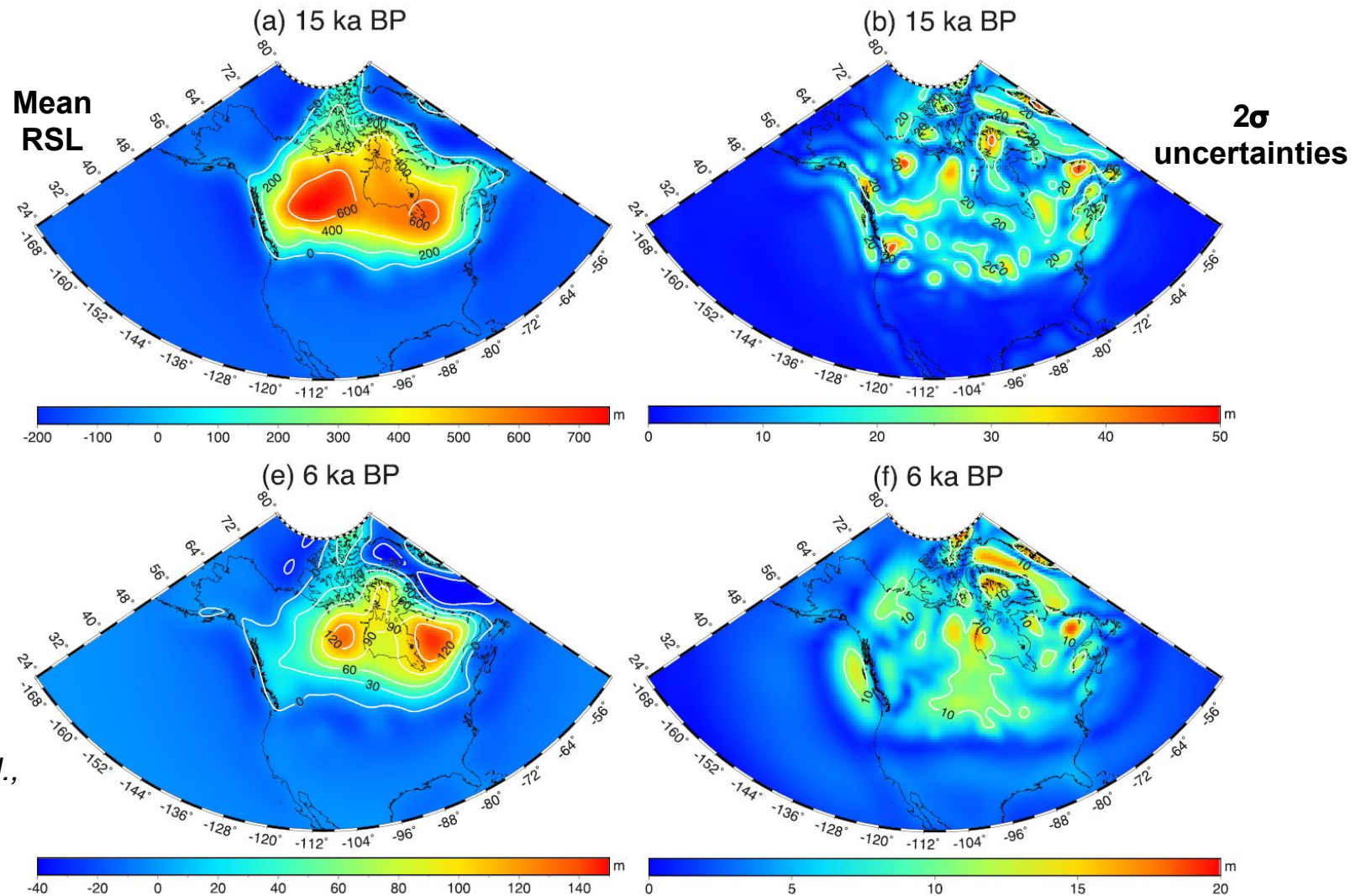
GMSLR is affected by T2 GIA uncertainties at the 0.2 mm/yr level:

$$\mu = (1.58 \pm 0.38) \text{ mm/yr} \quad \rho = (\mu - \gamma) = (1.4 \pm 0.6) \text{ mm/yr}$$

Input uncertainties at the regional scale: the role of 3D structure

Li et al. (2020) quantified GIA model uncertainties in North America associated with 3D viscosity structure in the lower mantle and laterally varying lithospheric thickness.

Present-day peak uncertainties in the Hudson Bay are ~ 2.4 mm/yr



From Li et al.,
GRL, 2020

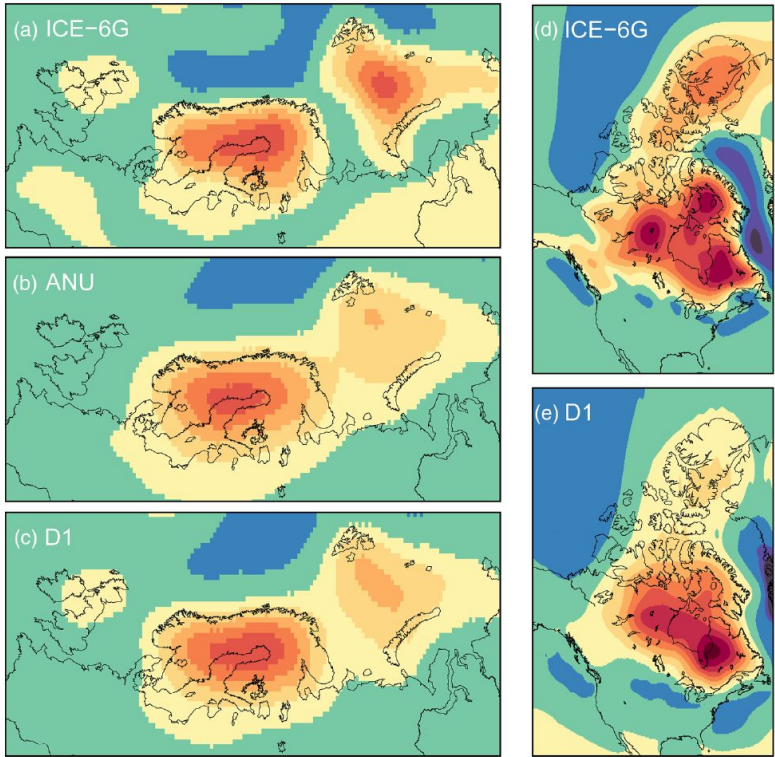
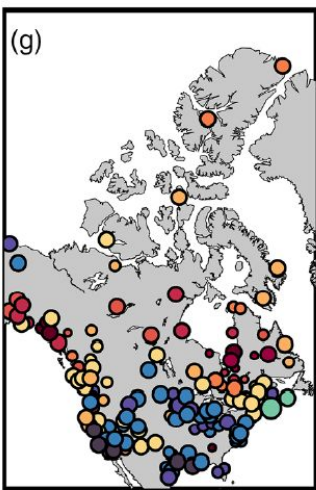
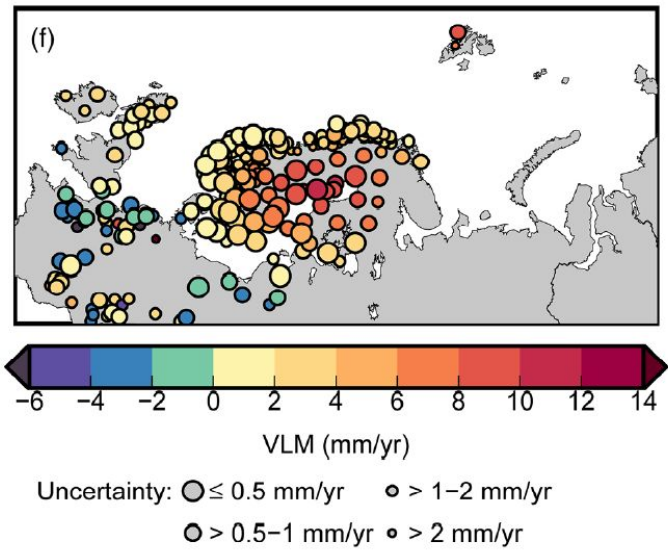
Structural uncertainties at the regional scale

Simon & Riva (2020) compared a suite of GIA models and uncertainty estimation across North America and Fennoscandia.

Within deglaciation centers, GIA model uncertainty is up to ~2 mm/yr

Away from the former ice sheet centers, GIA uncertainty for relative sea level change is ~0.3–0.5 mm/yr along the U.S. East Coast and ~0.6–0.8 mm/yr in the North Sea.

From Simon and Riva, JGR, 2020



Conclusions

- We have identified two possible sources of uncertainties in GIA modeling:
 - **Input uncertainties (T1)**, stemming from imperfect knowledge of basic model parameters
 - **Structural uncertainties (T2)**, related to different methodological approaches to the problem and/or different data sets used to constrain the model

The distinction between T1 and T2 maybe somewhat blurred.

- At TGs located at the margins of former ice sheets **both types of uncertainties exceed those associated to observed rates.**
- **A major result is that GMSLR is only marginally affected by GIA uncertainties**, while at regional scale they can be significant.
- At present, a **rigorous assessment of T2 uncertainties is hindered** by available computational power and by the limited number of independently developed, testable global GIA models.

Thanks for your attention!