Glacial isostatic adjustment observations and modeling

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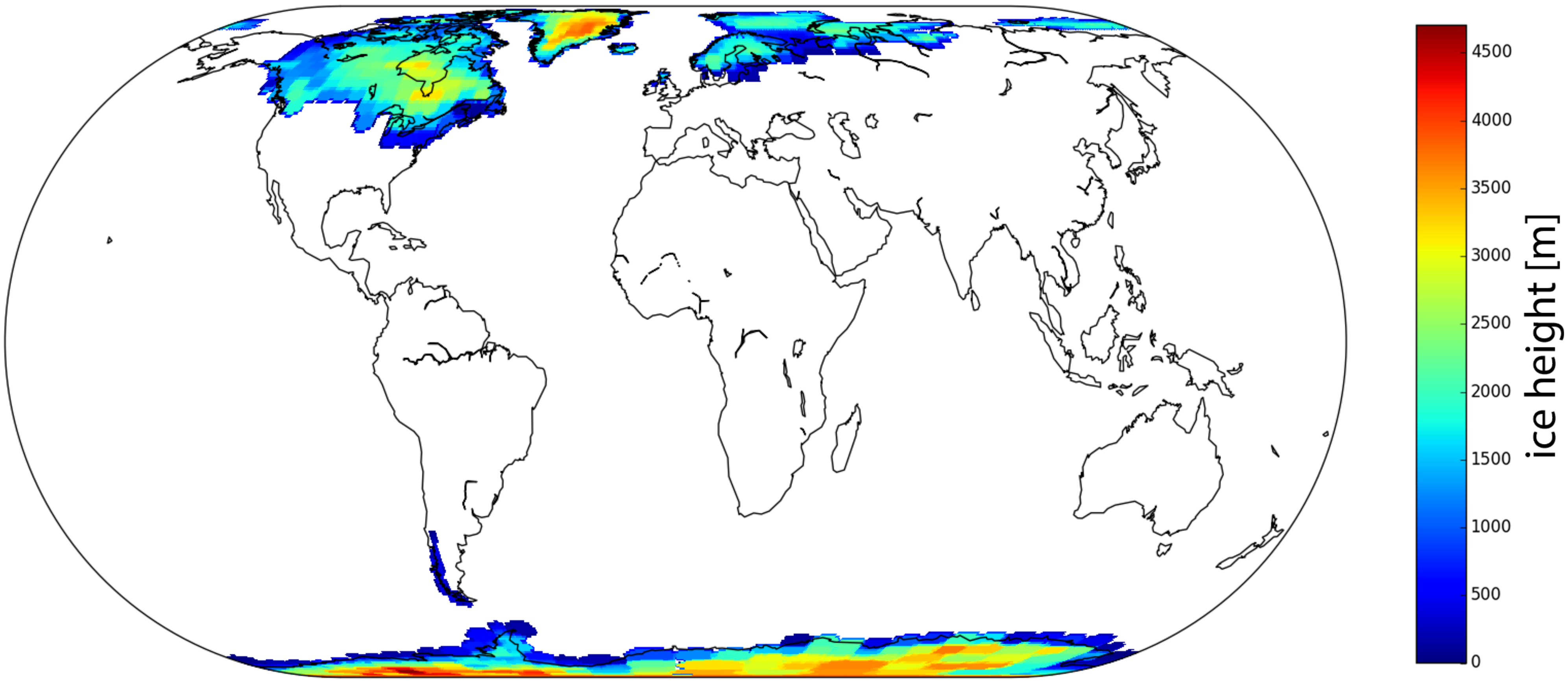
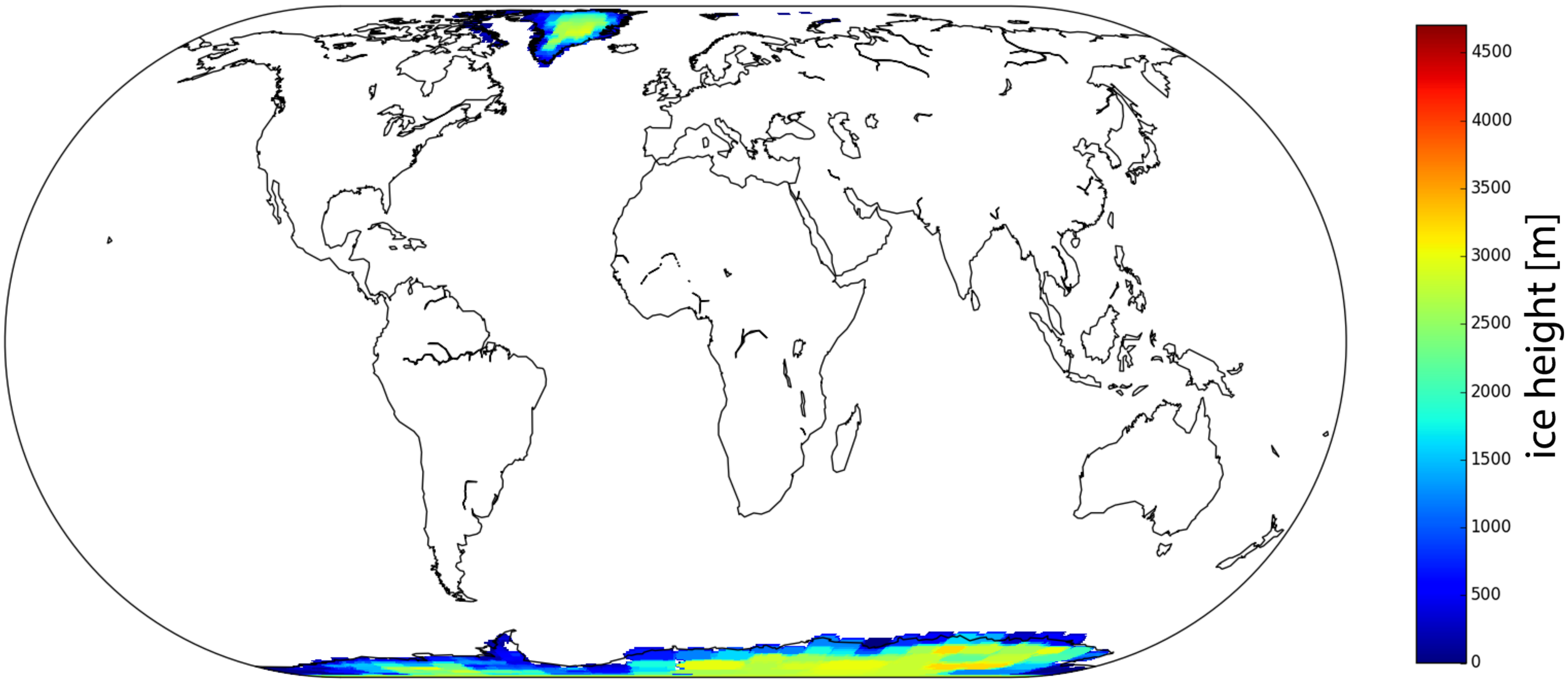
GEO-DEEP9300, 3.11.2021

Ice heights at Last Glacial Maximum (LGM)



Tushingham and Peltier (1991)

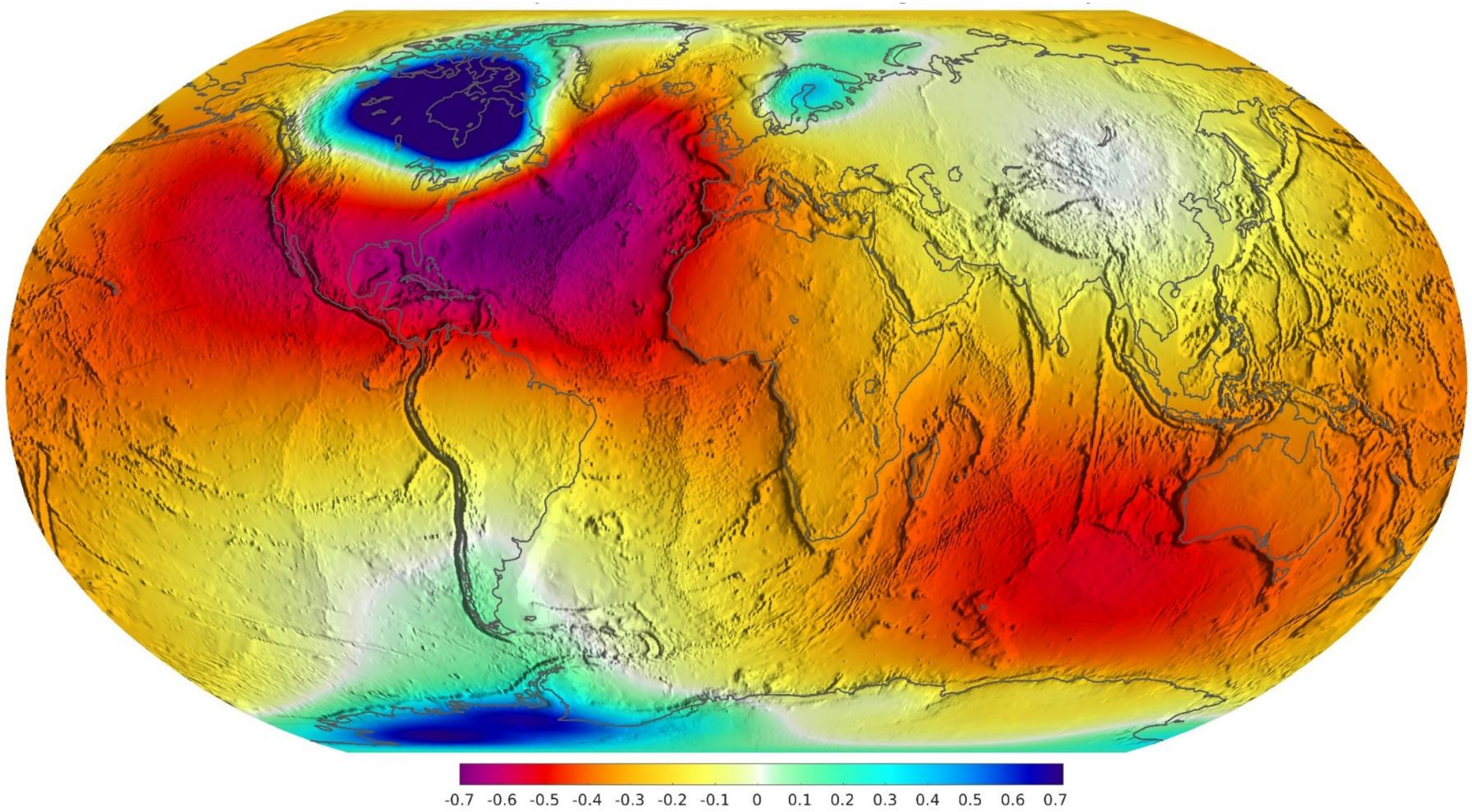
Ice heights at present day



Tushingham and Peltier (1991)

Glacial isostatic adjustment (GIA) model

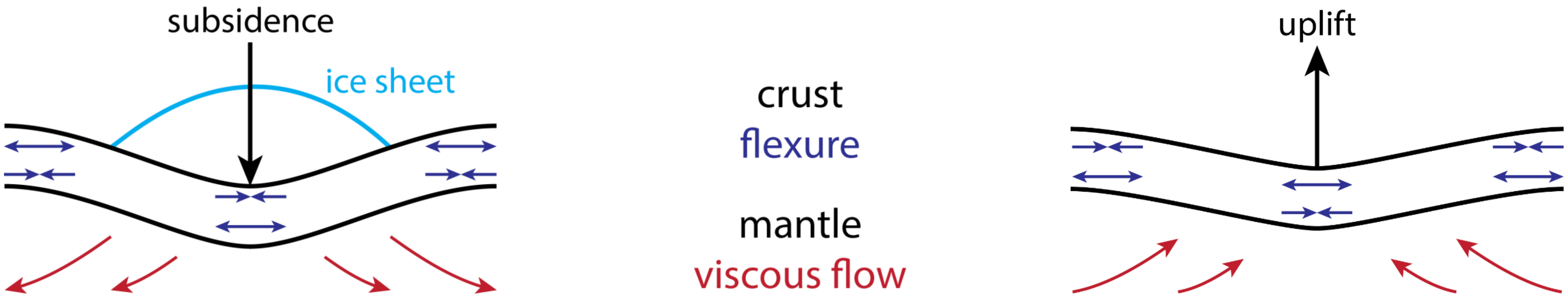
Uplift rate [mm /yr]



Peltier et al. (2018)

Glacial isostatic adjustment (GIA)

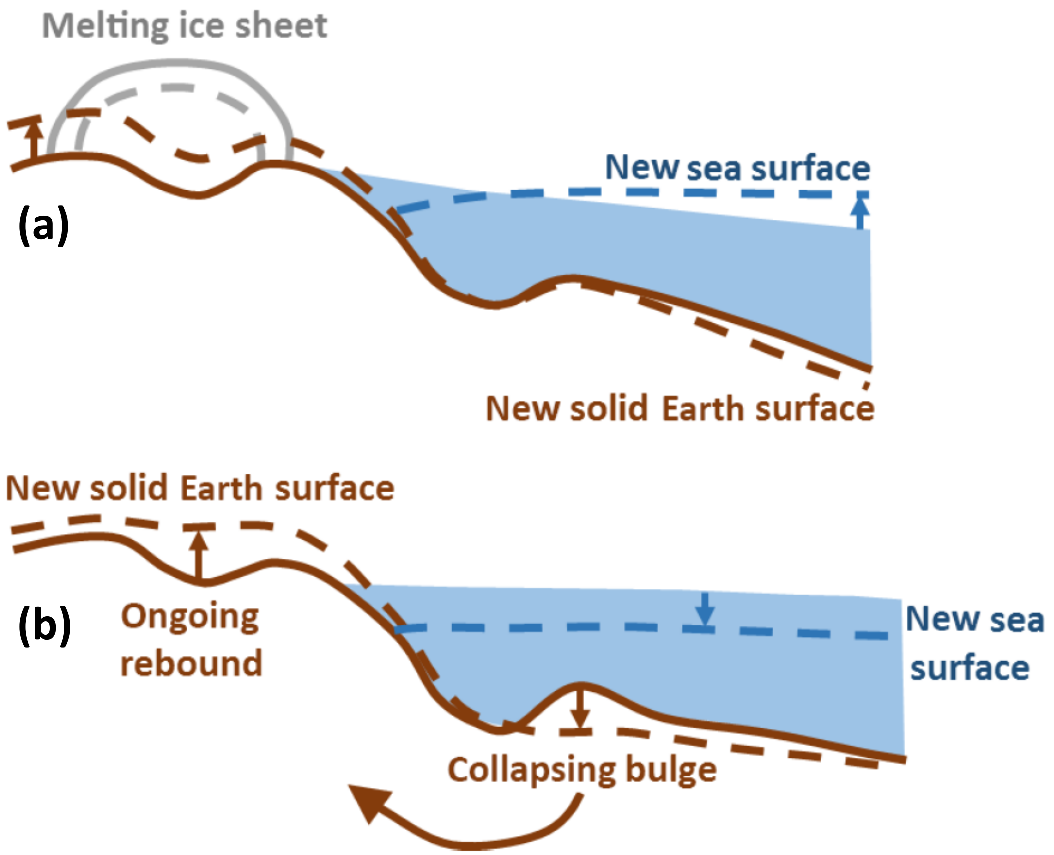
- Isostasy: equilibrium state between the crust and mantle (buoyancy vs. gravity)
- Isostatic adjustment: deformation taking place to restore the earth to an equilibrium state
- Glacial isostatic adjustment (GIA): isostatic adjustment related to ice and water loading



Modern field of GIA addresses:

- Solid Earth response to surface load changes by ice and ocean water
- Gravitationally consistent redistribution of seawater across the global ocean

GIA and sea level



Start situation

- Subsidence of crust underneath ice sheet
- Creation of peripheral forebulges
- Sea level higher towards ice sheet due to gravitational attraction

(a) Elastic (instantaneous) response due to ice melt

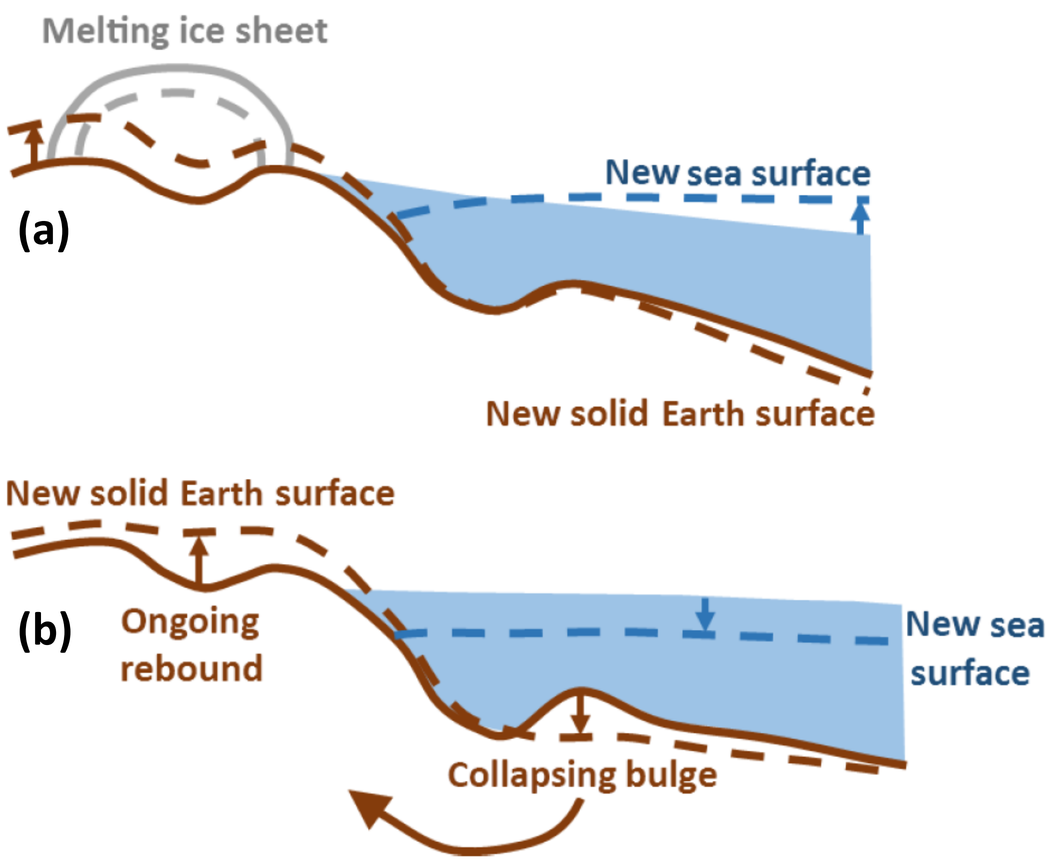
- Crust beneath ice sheet experiences uplift
- Global sea level rise due to ocean water increase
  - Sea-level drop close to ice sheet
  - Additional sea-level rise in the far field

(b) Viscous (long-term) response due to ice melt

- Ongoing solid Earth relaxation
  - Uplift underneath disappeared ice sheet
  - Collapse of peripheral forebulges
- Ocean floor subsidence due to ocean load increase and collapsing forebulges: decrease in mean sea level

Whitehouse (2018), adapted from Conrad (2013)

GIA and sea level



- Redistribution of seawater over the oceans is not uniform
- Gravitational field continuously changes due to:
  - Changes in glacial loading
  - Changes in oceanic loading
  - Deforming solid Earth due to changes in glacial and oceanic loading
- Geoid, equipotential surface that defines the global mean sea level, responds accordingly

Whitehouse (2018), adapted from Conrad (2013)

GIA and climate change

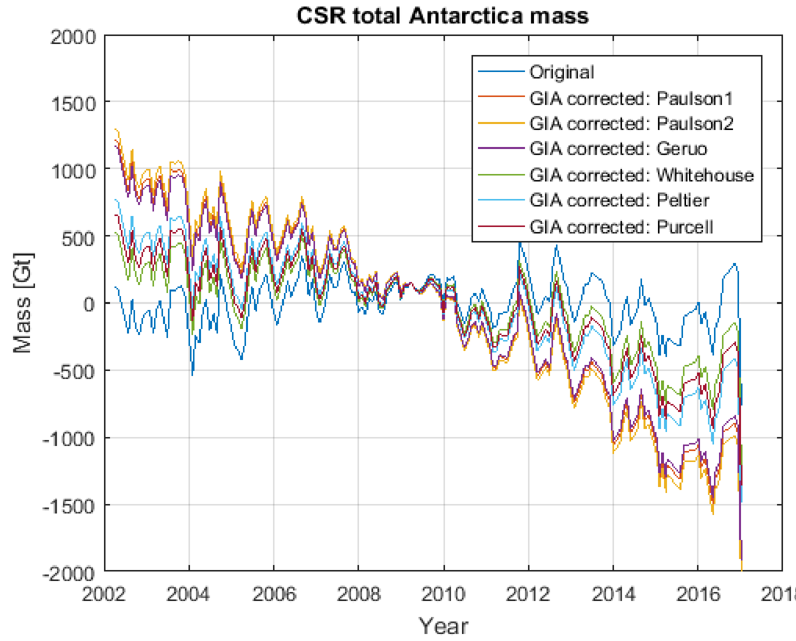
- The Earth is still deforming from ice that is long gone (viscous response), but also from contemporary ice change (elastic response)!

- Geodetic observations are ‘contaminated’ by GIA
  - GNSS: vertical land motion
  - Altimetry: absolute sea level
  - Tide gauges: relative sea level
  - Gravimetry: mass changes

- Especially interesting in areas with present-day ice melt: Greenland and Antarctica

- In order to find signals related to current climate change, these geodetic observations need to be corrected for GIA

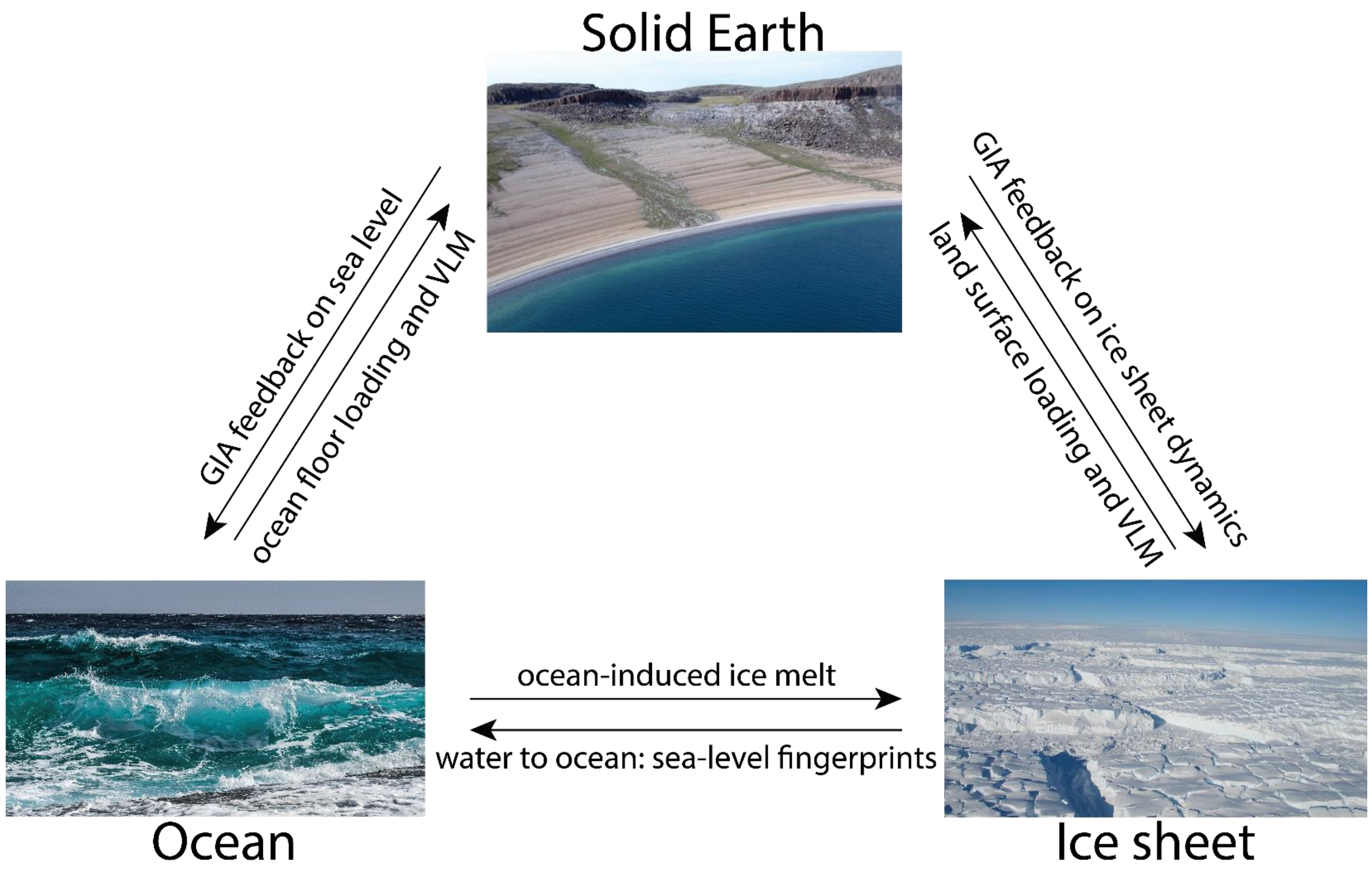
GRACE: Gravity Recovery and Climate Experiment



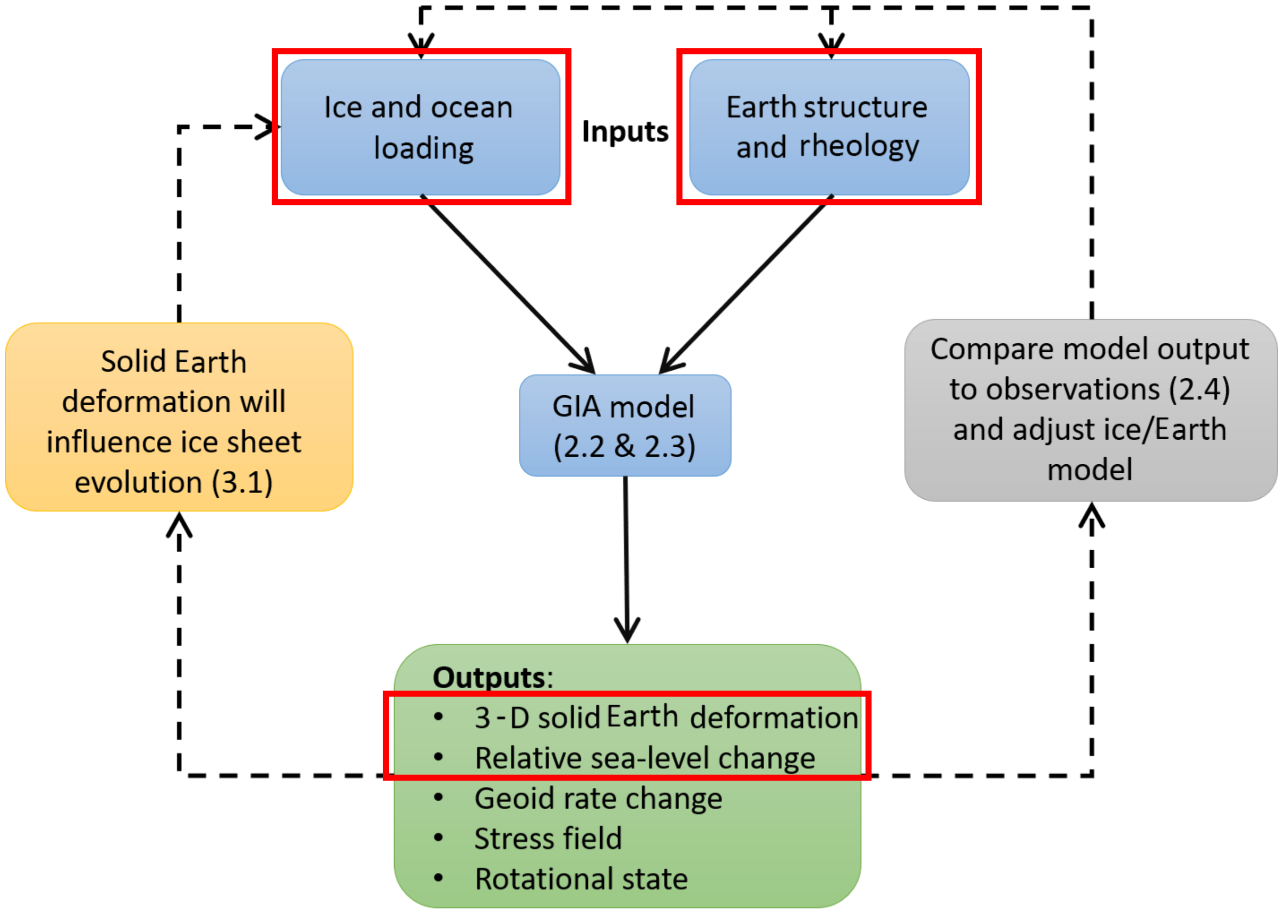
GIA corrected Antarctic ice mass loss estimates:
-60 to -150 Gt/yr

(upper: Astrium/GFZ, lower: Weerdesteijn, 2017)

Solid Earth, ice sheet, and ocean interactions



GIA modeling

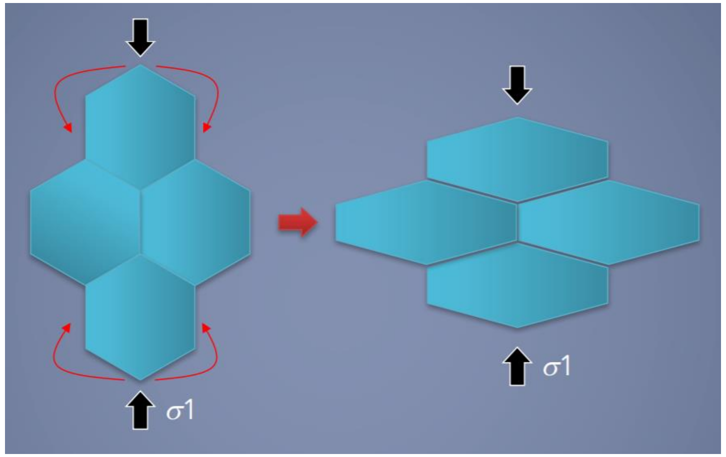


Whitehouse (2018)

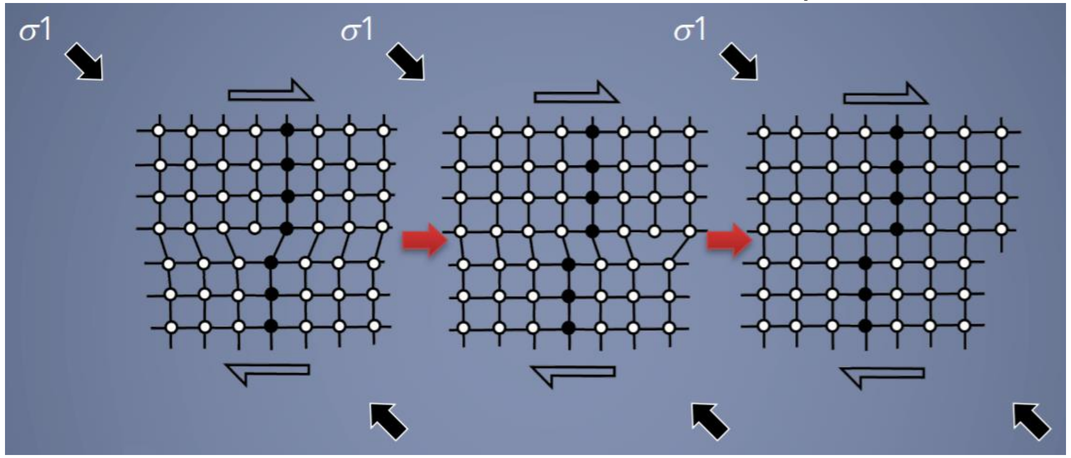
GIA modeling inputs: Earth rheology

- Elastic lithosphere
- Viscoelastic mantle
  - Flow laws: linear or non-linear relation between strain rate and stress
  - Low stress level / small grain size → diffusion creep: linear flow law
  - High stress level / large grain size → dislocation creep: non-linear flow law
  - Composite rheology: both diffusion and dislocation creep

Linear diffusion creep



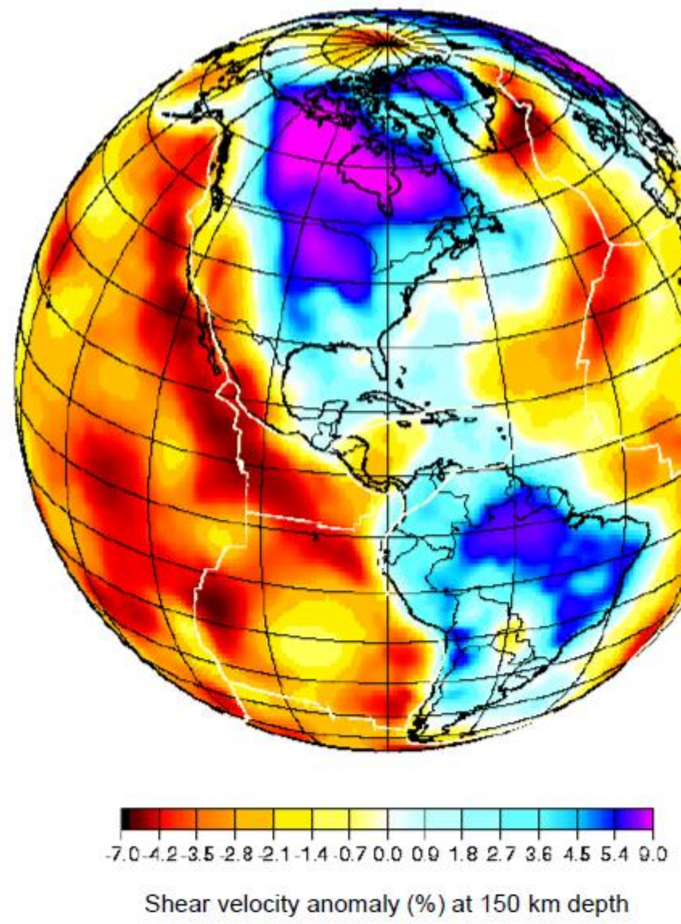
Non-linear dislocation creep



Skemer (2017)

GIA modeling inputs: Earth rheology

- Measuring viscosity from seismology
  - Spatial variations can be mapped in great detail
  - Seismic attenuation and velocity anomalies: highly correlated
  - Velocity anomalies → temperature variations → viscosity
  - Temperature to viscosity conversion methods all have their weaknesses:
    - Poorly constrained variables: Viscosity = f(temperature, composition, grain size, water content, partial melt)
    - No inclusion of non-linear rheologies
    - Body wave tomography underestimates seismic anomalies due to lack of depth resolution
    - Etc.

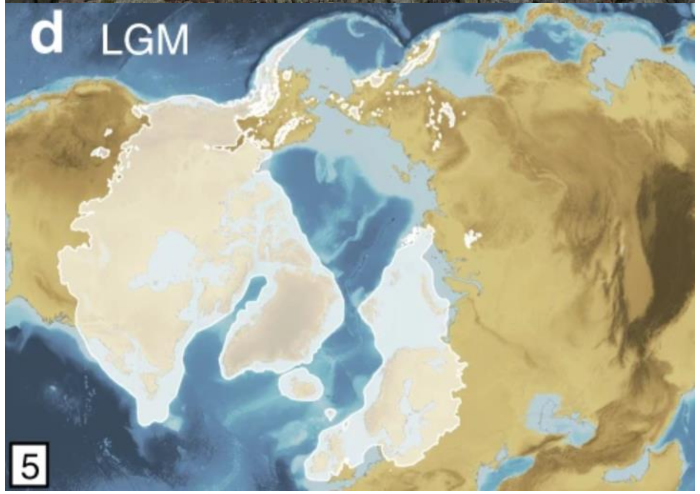


Shapiro and Ritzwoller (2002)

GIA modeling inputs: ice history

1. Extent of ice cover
   - Dating of moraines
   - Geomorphological mapping
2. Thickness of ice cover
   - Oxygen isotope records and isotope-elevation relations
   - Glaciological and geophysical models
   - Global ice volume estimate from relative sea level in the far field and GIA

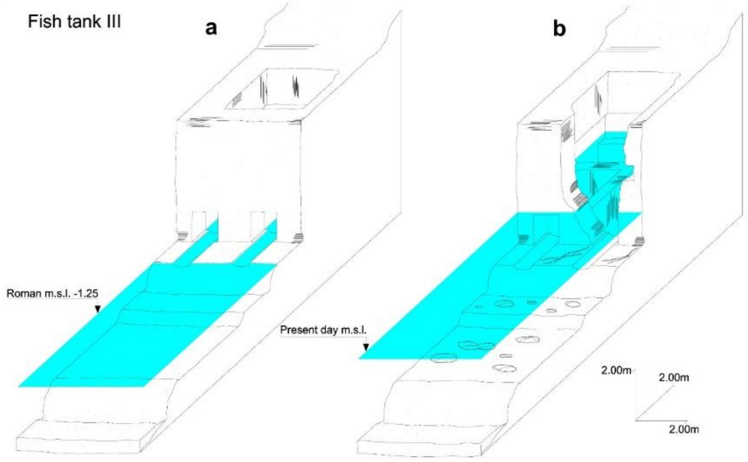
- Previous glaciations harder to constrain due to replacement of evidence from more recent deglaciations



Moraine at Baltic coast (top), raised shoreline Sweden (middle), ice extent at LGM: Batchelor et al. (2019) (bottom)

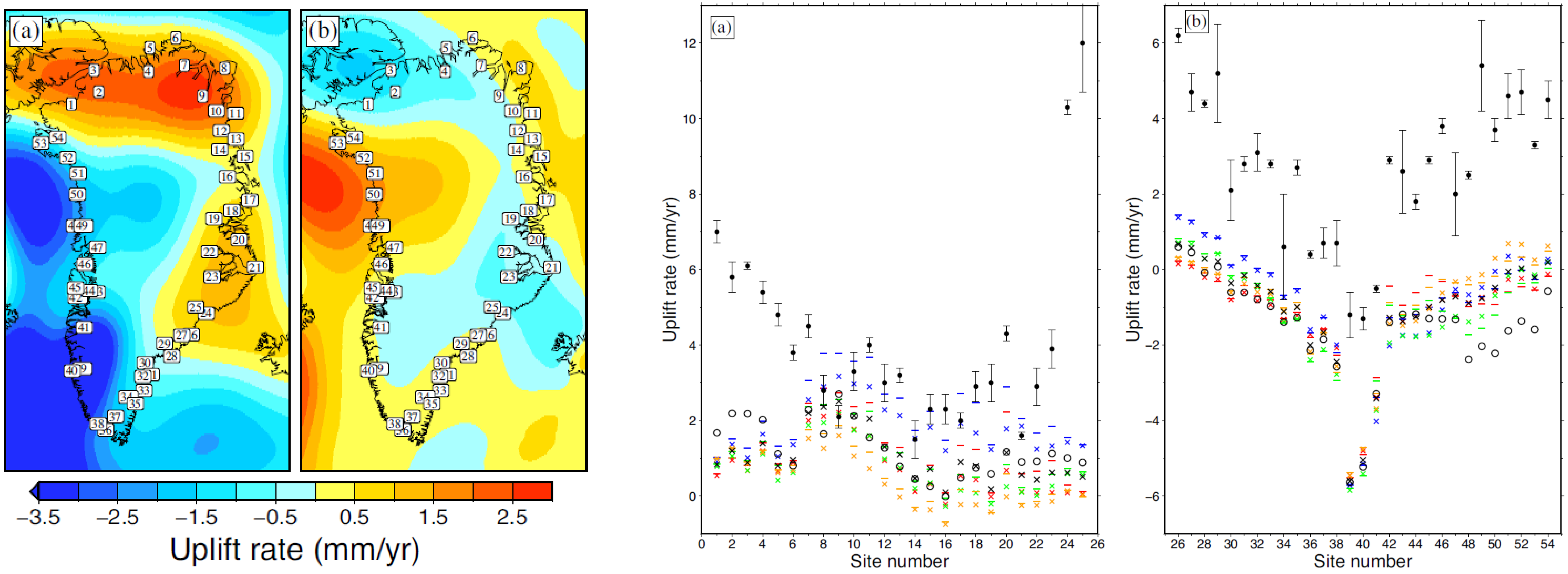
GIA modeling outputs: RSL

- Sea level index point (SLIP): estimate of RSL at certain time and place and its uncertainty
  - Dating of paleoshorelines or other indicators: carbon or cosmogenic nuclide dating of geomorphological or biological markers
  - Found in close proximity to present-day shorelines
- Upper limits: terrestrial
- Lower limits: marine
- Contemporary RSL: tide gauges ~100 yr bp



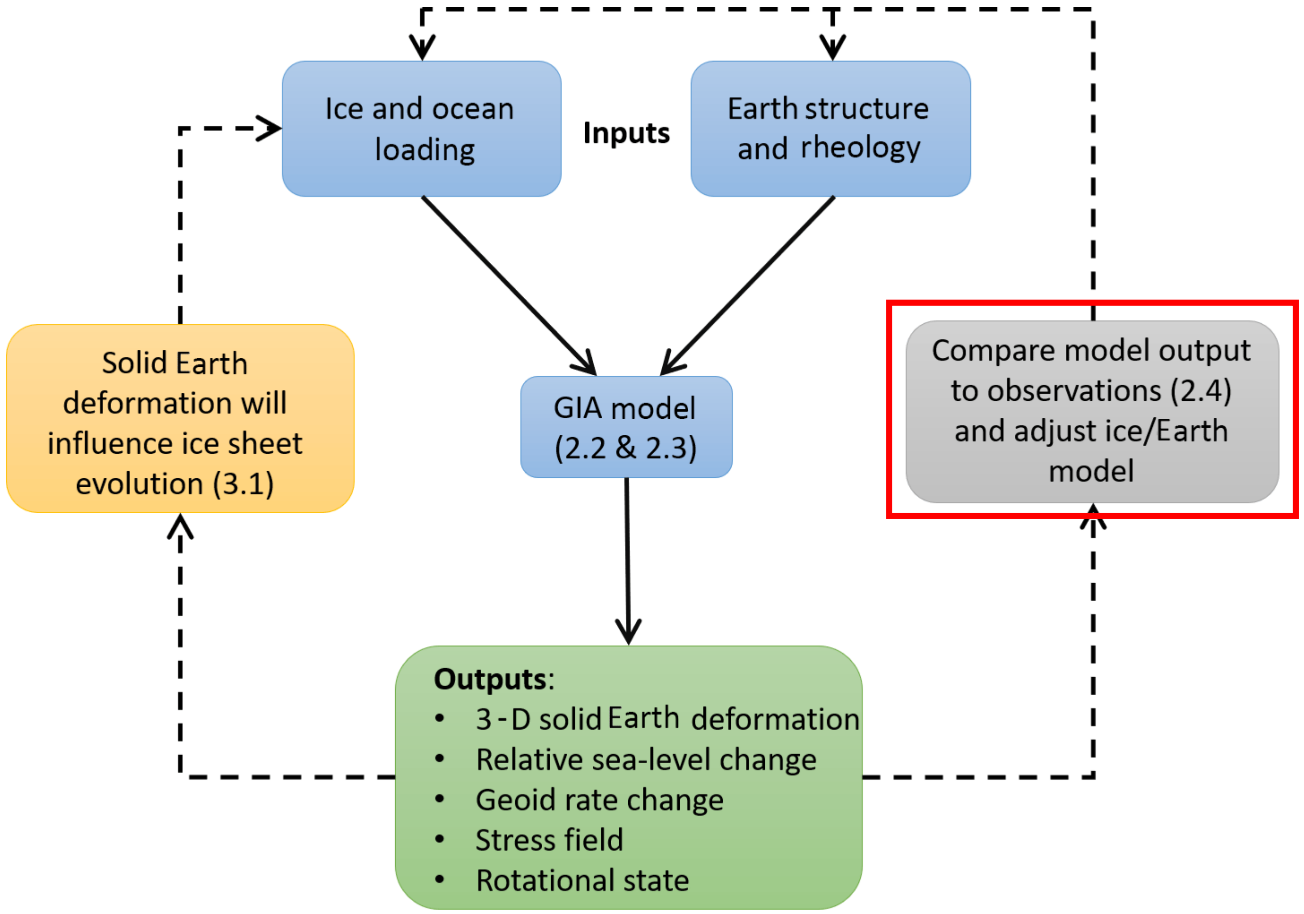
Moraine at Baltic coast (top), raised shoreline Sweden (middle), fish tanks: Mourtzas (2012) (bottom)

GIA modeling outputs: vertical land motion



Milne et al. (2018)

GIA modeling: recap



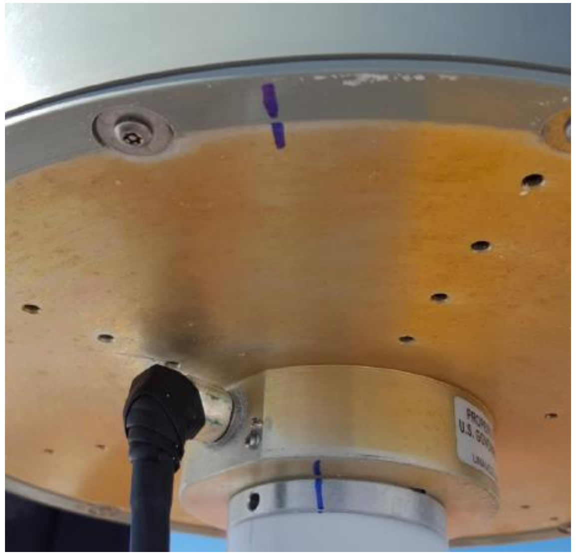
Whitehouse (2018)

- Tuning of input parameters within limits
- Non-uniqueness of model
- BUT ....


ANET POLENET: Wilson
Don’t take the observational data for granted….

GIA observations: use caution!

Initial



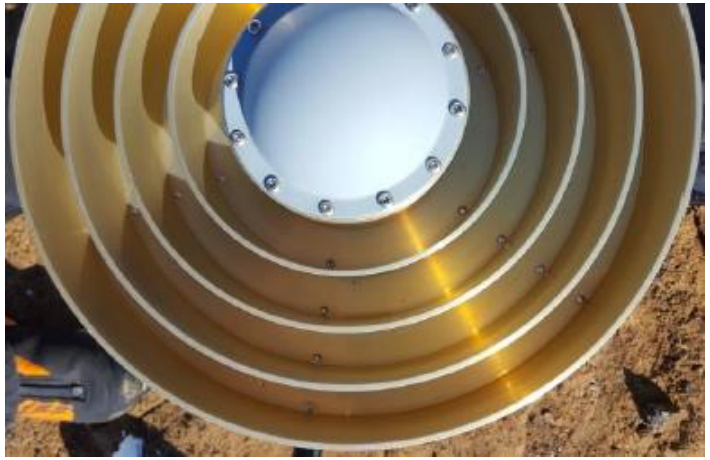
Post-tape

Post-plug

Ice accumulation

Less ice but liquid water traces

Clean!



Take home messages

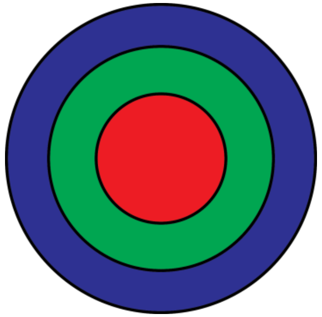
Models are not perfect, but observations aren’t perfect either

For GIA modeling and contemporary climate change studies:

we need both models and observations

GIA modeling: 1D vs. 3D

Homogeneous Earth
(radially symmetric)



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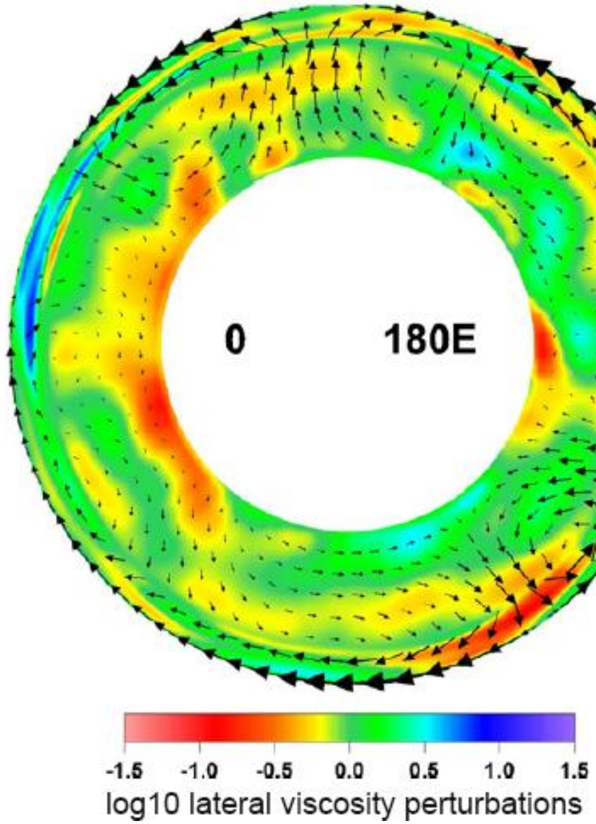
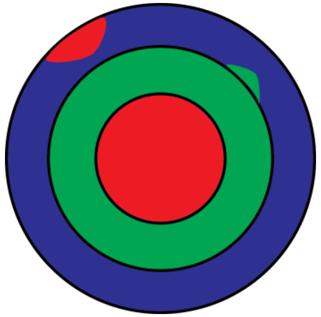
(Semi-)analytical



Kaban et al. (2006)

Heterogeneous Earth
(laterally varying)



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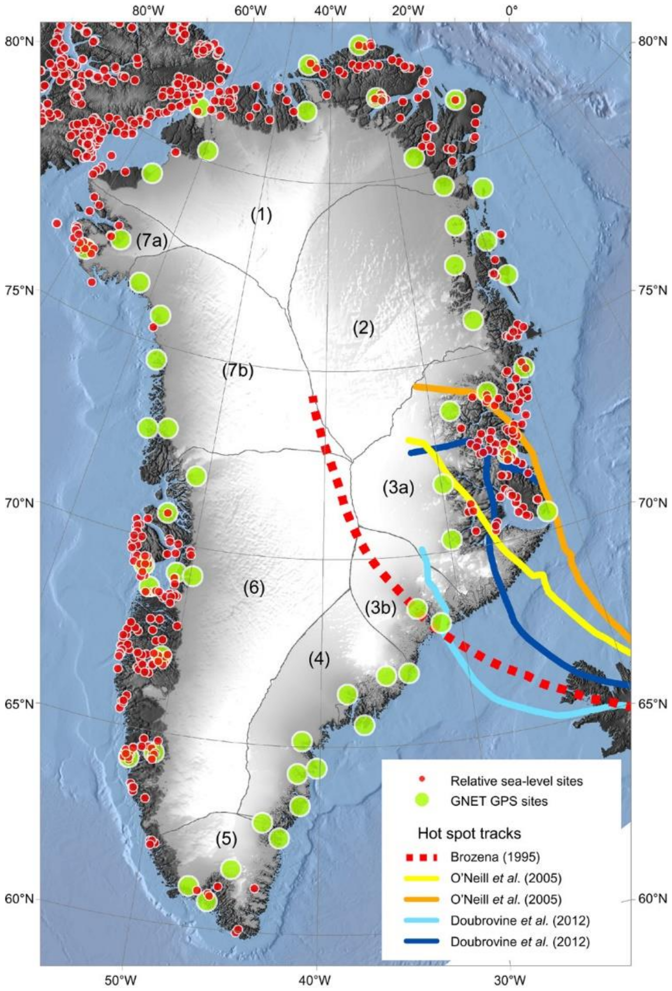
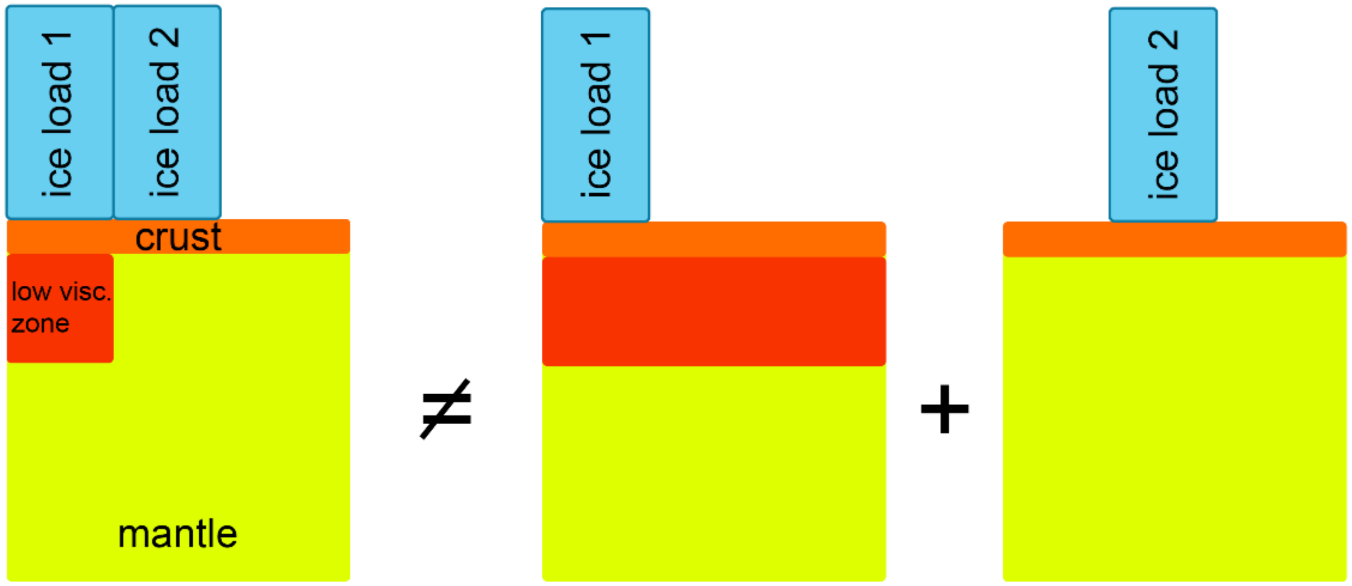
Numerical

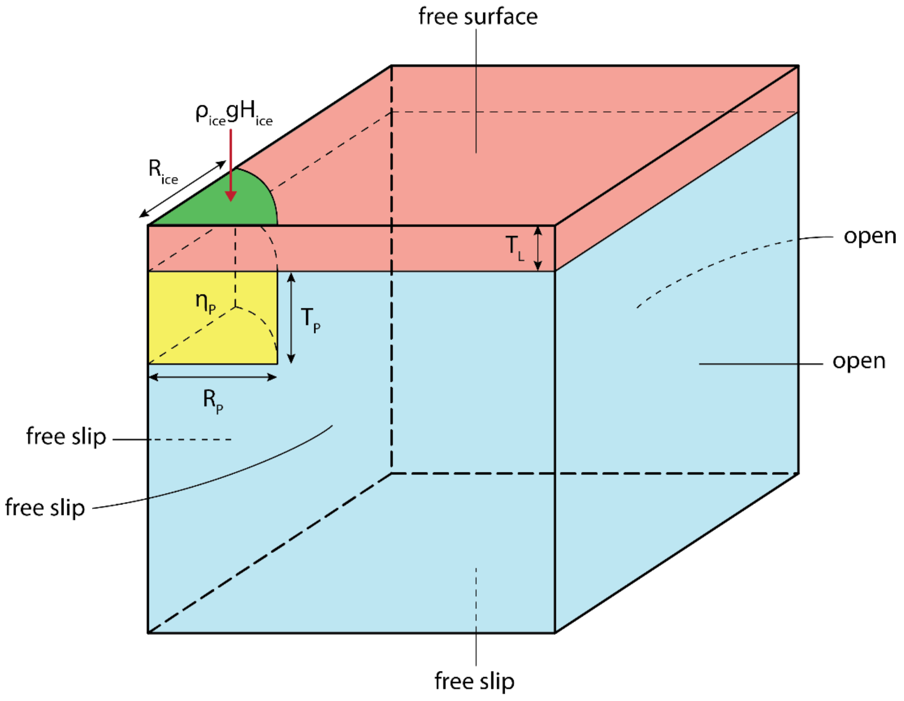
GIA modeling: 1D vs. 3D

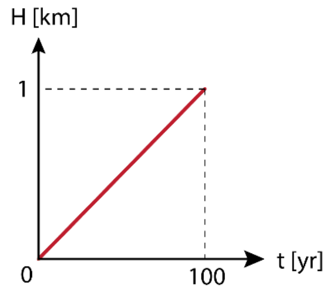


Khan et al. (2016)



3D model setup





Ice loading

ice height, H_{ice}	1 km
ice radius, R_{ice}	100 km
ice density, ρ_{ice}	931 kg/m^3

fixed parameters

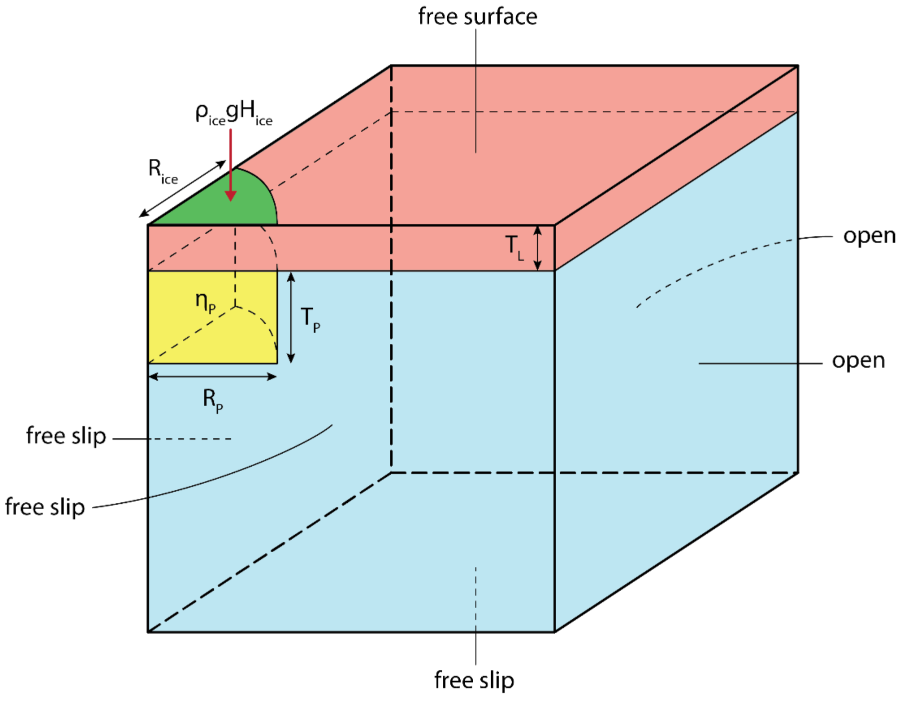
	viscosity, η [Pa s]	density, ρ [kg m^3]	shear modulus, μ [GPa]
mantle (M)	$5\cdot10^{20}$	4450	175
lithosphere (L)	$1\cdot10^{40}$	4450	45
pocket (P)	variable	4450	175

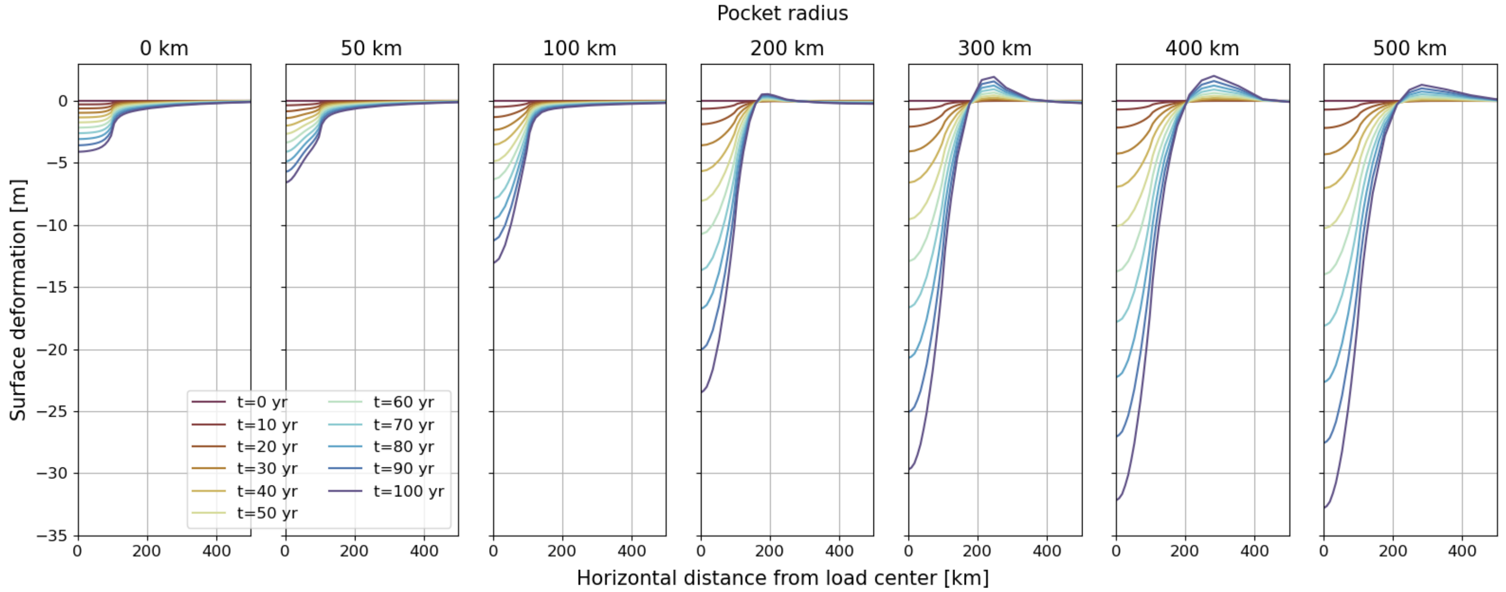
box geometry 500x500x500 km

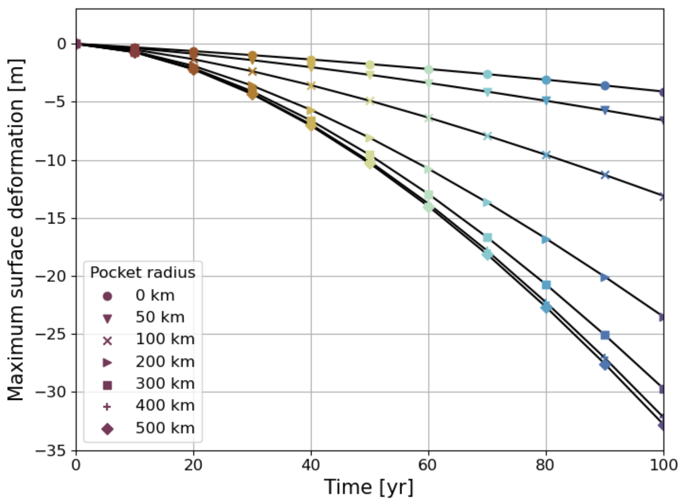
variable parameters (changing 1 parameter at a time)

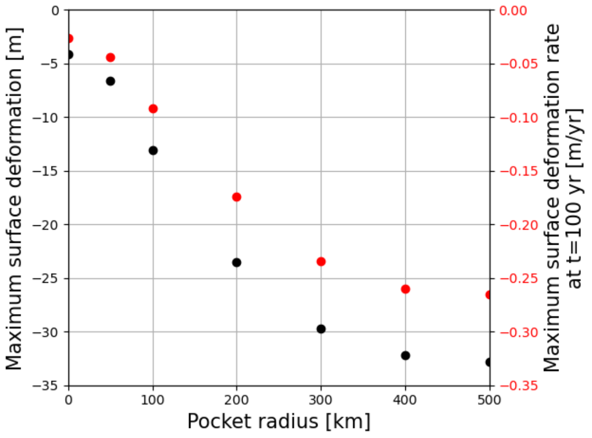
			REFERENCE VALUES				
pocket viscosity, η_P [Pa s]	$1\cdot10^{18}$	$5\cdot10^{18}$	$1\cdot10^{19}$	$5\cdot10^{19}$	$1\cdot10^{20}$		
pocket radius, R_P [km]	0	50	100	200	300	400	500
pocket thickness, T_P [km]	0	50	100	200	300	400	500
lithospheric thickness, T_L [km]	15	30	45	60	75		

Pocket radius effect on surface deformation

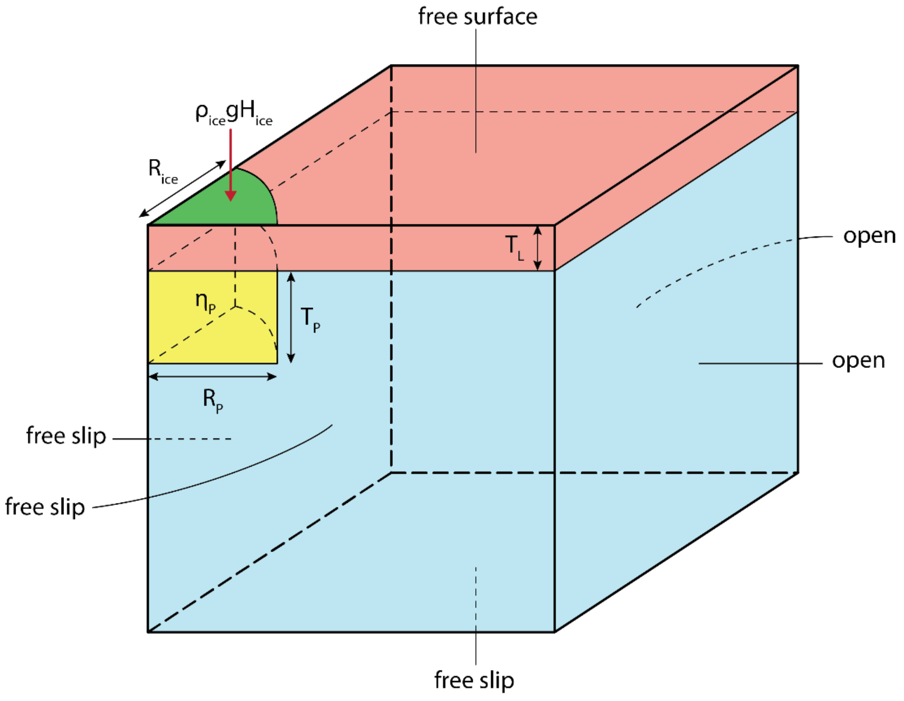


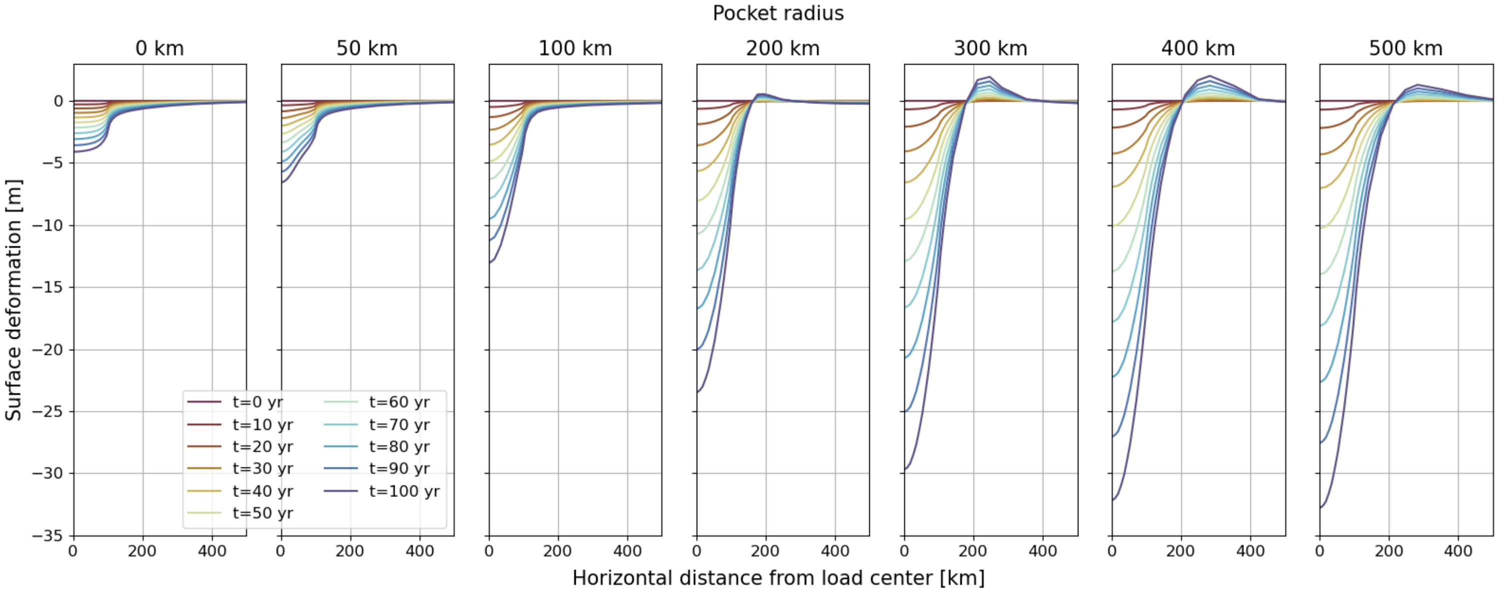


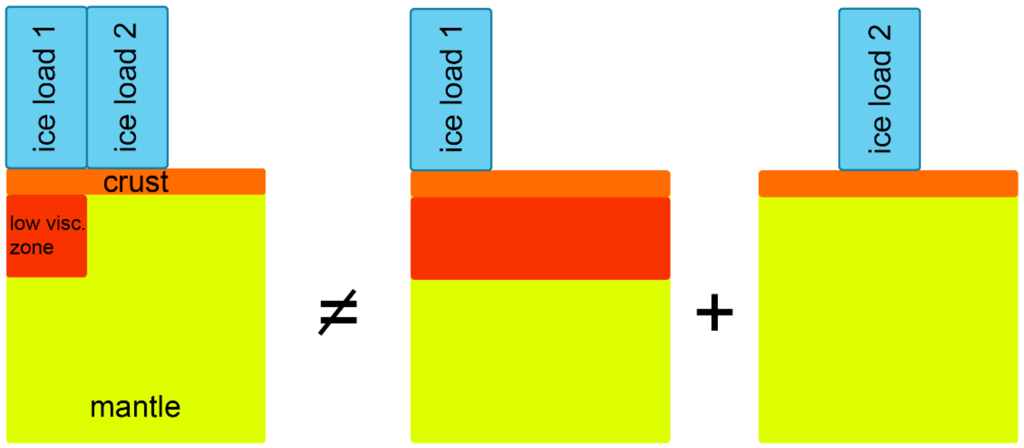




Pocket radius effect on surface deformation







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3D GIA modeling is the way forward!

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