CSQ-33 Summary

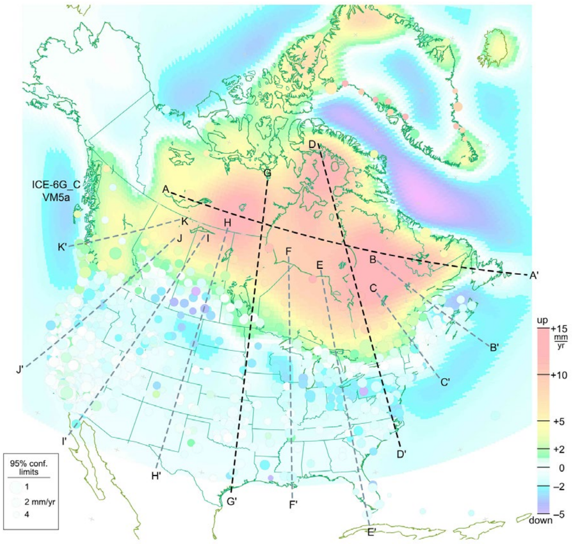
Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How does the solid Earth deform under present and past ice loads and what does it tell us about its rheology ?	A) Quantify the long-term GIA signal of the Pleistocene deglaciation in ice sheet elevation and gravity field in regions of present-day ice caps melting, and separate it from contributions reflecting ice sheet imbalance and from GIA responses to the Little Ice Age.	• geomorphological data (past ice mass extent) • cosmogenic exposure dating and local sampling (past ice mass thickness) • GNSS and InSAR (surface deformation due to present-day ice load and mantle relaxation to past ice loads) • gravimetry (mass changes due to present-day ice load and mantle relaxation to past ice loads), altimetry (ice volume) • seismology (lithospheric thickness)	• High accuracy over medium to high spatial resolutions to enhance ice vs GIA signals separation and combination of different types of observations • Gravity: 10 cm EWH* /yr, spatial scale < 100 km (wish). • Continuity over time to separate inter-annual variations from long-term trends. • Coverage of polar areas • Multi-satellite missions with orbit inclination choice can help to improve gravity recovery.	Models of visco-elastic mantle relaxation under a surface load. Need for models able to account for 3D variations in physical properties of the Earth (not only radial). Algorithms for source separation in geodetic data	Assess the contributions of glaciers and ice caps to global mass balance estimates, which constitute an important tool to understand present climate variations Understand the causes of sea level variations and assess the contributions of glaciers and ice caps.
	B) Quantify the solid Earth visco-elastic response to recent or contemporary ice mass change	• Same as above	• Same as above, with an emphasis	Models of visco-elastic mantle relaxation under a surface load.	

	in glaciated regions associated with low mantle viscosity, such as active plate boundaries.		towards higher spatial resolutions.	Need for models able to account for 3D variations in physical properties of the Earth (not only radial). Algorithms for source separation in geodetic data.	
	C) Constrain the radial and lateral viscosity structure of the mantle (including in particular low viscosity layers and lateral variations between cratonic and oceanic areas or along hotspot tracks), from data-driven GIA models integrating a broad range of data types. In these models, describe the trade-offs between mantle structure and spatio-temporal evolution of the past ice load.	• Same as above		Models of visco-elastic mantle relaxation under a surface load. Need for models able to account for 3D variations in physical properties of the Earth (not only radial). Methods for data assimilation in GIA models.	

* EWH = equivalent water height

CSQ-33 Narrative

The solid Earth deforms both elastically and visco-elastically under the water/ice loads applied at its surface. It is still deforming today in response to past ice mass changes at different timescales, where the thickness of the lithosphere and the mantle viscosity influence the wavelength and the rate of the deformation. The main Glacial Isostatic Adjustment (GIA) signal reflects the upper and lower mantle viscous responses to the Pleistocene deglaciation. Smaller GIA signals result from relaxation processes at much shorter timescales due to the presence of low-viscosity regions in the mantle, and induced by more recent ice mass changes, over the last centuries (Little Ice Age). Because they change the topography of ocean basins and extend over the ice caps, these signals constitute a major source of uncertainty in order to understand the origin of the sea level variations and accurately estimate the mass balance of the ice caps. Global mass balance estimates based on satellite gravity are actually an important tool to understand present climate variations, which are reflected in present-day ice melting, a major contributor to sea level variations (IPCC, 2021). Assessing the contribution of glaciers and ice caps to these global mass budgets requires a precise GIA model. In addition, GIA signals bring one of the few observational constraints on the Earth's rheology and the mantle viscosity, a key parameter, yet not well understood, to model Earth's dynamics as well as the redistribution of stress at plate boundaries and in their interior. Building an accurate GIA model remains a challenge today (Whitehouse, 2018), because it requires knowledge on both the spatio-temporal evolution of the ice load, and the solid Earth rheology in 3D, taking into account low-viscosity layers and lateral viscosity variations between cratonic and oceanic areas, or along hotspot tracks. Future avenues consist in constraining GIA models from observations in regions, where the GIA signals are large but not well determined due to the superimposition with present-day ice melting (e.g. over the polar ice caps). Thus, the challenge is to co-estimate GIA and present-day ice mass balance using multi-technic approaches.



Uplift rate predicted by the ICE-6G GIA model over Northern America and Greenland (Peltier et al., 2015).

References

Whitehouse, P. L. (2018). Glacial isostatic adjustment modelling : historical perspectives, recent advances, and future directions, *Earth Surf. Dynam.*, 6, 401–429.

IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte V et al. (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

Peltier, W. R., D. F. Argus, and R. Drummond (2015). Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model, *J. Geophys. Res. Solid Earth*, 119, doi:10.1002/2014JB011176.