2.5 The Role of the Solid Earth for the Evolution of the Polar Ice Sheets

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Summary of session presentations and discussion

The thermal and mechanical structure of the solid earth exerts a primary control on the response of the polar regions to ice mass changes. Knowledge of the solid earth structure beneath the polar regions is thus needed to understand the evolution of the polar ice sheets. Specifically, the solid earth forms the lower boundary condition for ice dynamics, and it can affect glacial flow in two ways:

1. Geothermal Heat Flux (GHF) from Earth's interior provides heat input beneath the ice, which affects both the thermal balance of the ice sheet as well as the bed conditions (frozen or unfrozen) beneath the ice. Geothermal heat flow is difficult to measure beneath an ice sheet, and thus poorly constrained across most of Greenland and Antarctica.

2. Vertical motion of the bedrock beneath the ice sheets affects the bed slope of the ice sheet and the grounding line of marine-terminating outlet glaciers. Vertical ground motions in the polar regions can be rapid (up to several cm/yr) and are occurring due to Glacial Isostatic Adjustment (GIA). GIA is the process by which Earth's crust, lithosphere, and mantle deform as ice loads from the surface are repositioned by deglaciation. Estimates of GIA are important for constraining ice mass changes and sea level changes, both in the past and for the present-day. In most areas, rates of uplift due to GIA are uncertain, but recent geodetic observations are providing important new constraints.

The goal of this session was to discuss recent advances in understanding the structure of the solid Earth beneath the polar ice sheets, and to relate these structures to ice mass changes, vertical motion, and the dynamic response of ice sheets to the solid earth. We also focused on the observational aspects of the solid earth movement in the polar regions.

Geophysical observations can provide constraints on the density, temperature, and water content of the rocks in the upper mantle, improving our understanding of both GHF and GIA processes beneath the ice. Seismic observations are particularly important because seismic velocity depends strongly on the temperature of the rocks, which relates to both GHF and the rock properties (like viscosity) that determine GIA uplift rates. For Greenland, seismic models predict that the interior has a thick and stable lithosphere, from which we would infer low GHF. However, the Iceland plume has thermally influenced the southeast coast of Greenland, and possibly some of the Greenlandic interior as well. Generally, high GHF should accelerate melting beneath the ice, which would accelerate ice flow.

The seismic structure of the solid earth can also lead to constraints on the lithospheric thickness and the viscosity structure of the rocks beneath the ice. For example, seismically slow regions of the upper mantle, such as southeast Greenland or West Antarctica, are generally hotter and thus may have thinner lithosphere and/or lower upper mantle viscosity. Both attributes lead to much faster rates of GIA-induced ground uplift. Geophysical measurements, from magnetic, gravity, seismic, heat flow, geodetic, and magneto telluric observations, can also provide useful data that can be used to constrain lithospheric thickness and/or mantle viscosity structure.

For a given mantle structure and an estimated ice load history, numerical models of the GIA process can provide useful predictions of uplift rates. Such models are necessary to relate observations from ground and satellite observations to rates of ice-mass loss. GIA models produce dramatically different results for different lithospheric thicknesses and different viscosities beneath the lithospheric plates, and thus 3D GIA modelling efforts are required. Uplift rates from modern deglaciation can be quite large (a few cm/yr) if deglaciation is rapid and the upper mantle is weak (low viscosity). This may be the case beneath southeast Greenland (e.g., Kangerlussuaq Glacier), where GNSS (Global Navigation Satellite Systems) observations of rapid uplift are consistent with a mantle that was heated by the Iceland Plume.

If GIA processes are uplifting the ground surface rapidly, then this uplift can move the grounding line of outlet glaciers seaward. This can potentially stabilize the catchment area of the glacier, but ice sheet stability depends significantly on the interaction between rock uplift, ice sheet mass loss, and ocean interaction with the glacier tongue. Coupled GIA – ice sheet models indicate that grounding line retreat in West Antarctica can be delayed by 50 – 130 years when GIA uplift above a hot upper mantle is included, leading to a 9-23% reduction in the Antarctic sea-level contribution by the year 2500. This impact of the solid Earth feedback onto ice sheet projections can be twice as large as the uncertainty due to the climate forcing.

Geodetic constraints are essential for understanding the all-important link between GIA-induced ground uplift and ice sheet dynamics. Right now, networks of GNSS stations collect real-time uplift data across Greenland and Antarctica, and such constraints are essential for understanding how rapid uplift and ice sheet deglaciation processes interact, with implications for future stability of the ice sheet. However, the future of these networks is uncertain. The large expense of station installation and subsequent maintenance have led to questions about the future of some station networks. For example, the future of the POLENET stations in Antarctica (currently supported by funding from the USA) are discussed to be decommissioned due to missing funding in the future. Overall, continuous international support of polar GNSS networks is essential for ice sheet monitoring.

Advancements and highlights

- Improvement of geophysical constraints on the solid Earth structure, by combining ground- and space-based datasets.
- Advancement of 3D GIA modelling capabilities by incorporating realistic Earth model variations as well as sophisticated rock deformation behaviour (i.e., non-linear rheologies and compressibility).

KEY MESSAGES AND RECOMMENDATIONS

- Enhancement of the coupling between ice sheet dynamic models and 3D GIA models, specifically incorporating lithospheric as well as upper and lower mantle structures.
- Expansion and continuation of bedrock displacement observations in the polar regions, e.g. from GNSS stations and measurements from space such as InSAR (Interferometric Synthetic Aperture Radar), to improve estimates of GIA models.