Rapid ice unloading in the Fleming Glacier region, southern Antarctic Peninsula, and its effect on bedrock uplift rates

Rapid regional warming in the Antarctic Peninsula has led to the significant retreat and eventual collapse of several major ice shelves since the 1970s, triggering the subsequent acceleration and thinning of their feeding glaciers. The Wordie Ice Shelf, lying off the west coast of the Antarctic Peninsula, has undergone long-term disintegration since the 1960s with a substantial calving event occurring around 1989, followed by continuous steady retreat and its almost-complete disappearance. The dynamic response of the upstream glaciers to the ice shelf collapse and the response of the solid Earth to the associated mass loss are not fully understood. To quantify the mass loss from the system, we generated a digital elevation model (DEM) using airborne vertical and oblique imagery from 1966 and compared it to a DEM derived from 2008 SPOT data. This analysis reveals lowering over that time of approximately 60 m at the front of Fleming Glacier. Using IceBridge and ICESat-2/GLAS data spanning 2002–2014, we show an increased rate of mean ice-surface lowering, with rates post-2008 more than twice those of 2002–2008. We use these load change data as a basis for the simulation of viscoelastic solid Earth deformation. We subtract modeled elastic deformation rates, and a suite of modeled viscous rates, from GPS-derived three-dimensional bedrock velocities at sites to the south of Fleming Glacier to infer properties of Earth rheology. Assuming the pre-breakup bedrock uplift was positive due to post-Last Glacial Maximum (LGM) ice retreat, our viscoelastic-corrected GPS uplift rates suggest upper mantle viscosities are >2×10^{19} \text{ Pas} and likely >1×10^{20} \text{ Pas} in this region, 1–2 orders of magnitude greater than previously found for the northern Antarctic Peninsula. Horizontal velocities at the GPS site nearest the Fleming Glacier, after the application of elastic and plate tectonic corrections, point away from Marguerite Bay rather than the present glacier front. This suggests that horizontal motion in the region reflects the earlier retreat of the glacier system following the LGM, compatible with a relatively strong mantle in this region. These findings highlight the need for improved understanding of ice load changes in this region through the late Holocene in order to accurately model glacial isostatic adjustment.

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Short-term variations of Icelandic ice cap mass inferred from cGPS coordinate time series

As the global climate changes, understanding short-term variations in water storage is increasingly important. Continuously operating Global Positioning System (cGPS) stations in Iceland record annual periodic motion—the elastic response to winter accumulation and spring melt seasons—with peak-to-peak vertical amplitudes over 20 mm for those sites in the Central Highlands. Here for the first time for Iceland, we demonstrate the utility of these cGPS-measured
displacements for estimating seasonal and shorter-term ice cap mass changes. We calculate unit responses to each of the five largest ice caps in central Iceland at each of the 62 cGPS locations using an elastic half-space model and estimate ice mass variations from the cGPS time series using a simple least squares inversion scheme. We utilize all three components of motion, taking advantage of the seasonal motion recorded in the horizontal. We remove secular velocities and accelerations and explore the impact that seasonal motions due to atmospheric, hydrologic, and nontidal ocean loading have on our inversion results. Our results match available summer and winter mass balance measurements well, and we reproduce the seasonal stake-based observations of loading and melting within the 1 math formula confidence bounds of the inversion. We identify nonperiodic ice mass changes associated with interannual variability in precipitation and other processes such as increased melting due to reduced ice surface albedo or decreased melting due to ice cap insulation in response to tephra deposition following volcanic eruptions, processes that are not resolved with once or twice-yearly stake measurements.
An analytical solution for the elastic response to surface loads imposed on a layered, transversely isotropic and self-gravitating Earth

We present an analytical solution for the elastic deformation of an elastic, transversely isotropic, layered and self-gravitating Earth by surface loads. We first introduce the vector spherical harmonics to express the physical quantities in the layered Earth. This reduces the governing equations to a linear system of equations for the expansion coefficients. We then solve for the expansion coefficients analytically under the assumption (i.e. approximation) that in the mantle, the density in each layer varies as $1/r$ (where $r$ is the radial coordinate) while the gravity is constant and that in the core the gravity in each layer varies linearly in $r$ with constant density. These approximations dramatically simplify the subsequent mathematical analysis and render closed-form expressions for the expansion coefficients. We implement our solution in a MATLAB code and perform a benchmark which shows both the correctness of our solution and the implementation. We also calculate the load Love numbers (LLNs) of the PREM Earth for different degrees of the Legendre function for both isotropic and transversely isotropic, layered mantles with different core models, demonstrating for the first time the effect of Earth anisotropy on the LLNs.
Uplift rates from a new high-density GPS network in Palmer Land indicate significant late Holocene ice loss in the southwestern Weddell Sea

The measurement of ongoing ice-mass loss and associated melt water contribution to sea-level change from regions such as West Antarctica is dependent on a combination of remote sensing methods. A key method, the measurement of changes in Earth's gravity via the GRACE satellite mission, requires a potentially large correction to account for the isostatic response of the solid Earth to ice-load changes since the Last Glacial Maximum. In this study, we combine glacial isostatic adjustment modelling with a new GPS dataset of solid Earth deformation for the southern Antarctic Peninsula to test the current understanding of ice history in this region. A sufficiently complete history of past ice-load change is required for glacial isostatic adjustment models to accurately predict the spatial variation of ongoing solid Earth deformation, once the independently-constrained effects of present-day ice mass loss have been accounted for. Comparisons between the GPS data and glacial isostatic adjustment model predictions reveal a substantial misfit. The misfit is localized on the southwestern Weddell Sea, where current ice models under-predict uplift rates by approximately 2 mm yr\(^{-1}\). This under-prediction suggests that either the retreat of the ice sheet grounding line in this region occurred significantly later in the Holocene than currently assumed, or that the region previously hosted more ice than currently assumed. This finding demonstrates the need for further fieldwork to obtain direct constraints on the timing of Holocene grounding line retreat in the southwestern Weddell Sea and that GRACE estimates of ice sheet mass balance will be unreliable in this region until this is resolved.

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Rapid bedrock uplift in the Antarctic Peninsula explained by viscoelastic response to recent ice unloading

Since 1995 several ice shelves in the Northern Antarctic Peninsula have collapsed and triggered ice-mass unloading, invoking a solid Earth response that has been recorded at continuous GPS (cGPS) stations. A previous attempt to model the observation of rapid uplift following the 2002 breakup of Larsen B Ice Shelf was limited by incomplete knowledge of the pattern of ice unloading and possibly the assumption of an elastic-only mechanism. We make use of a new high resolution dataset of ice elevation change that captures ice-mass loss north of 66°S to first show that nonlinear uplift of the Palmer cGPS station since 2002 cannot be explained by elastic deformation alone. We apply a viscoelastic model with linear Maxwell rheology to predict uplift since 1995 and test the fit to the Palmer cGPS time series, finding a well-constrained upper mantle viscosity but less sensitivity to lithospheric thickness. We further constrain the best fitting Earth model by including six cGPS stations deployed after 2009 (the LARISSA network), with vertical velocities in the range 1.7 to 14.9 mm/yr. This results in a best fitting Earth model with lithospheric thickness of 100–140 km and upper mantle viscosity of $6 \times 10^{17}$–$2 \times 10^{18}$ Pas – much lower than previously suggested for this region. Combining the LARISSA time series with the Palmer cGPS time series offers a rare opportunity to study the time-evolution of the low-viscosity solid Earth response to a well-captured ice unloading event.
Effect of different implementations of the same ice history in GIA modeling

This study shows the effect of changing the way ice histories are implemented in Glacial Isostatic Adjustment (GIA) codes to solve the sea level equation. The ice history models are being constantly improved and are provided in different formats. The overall algorithmic design of the sea-level equation solver often forces to implement the ice model in a representation that differs from the one originally provided. We show that using different representations of the same ice model gives important differences and artificial contributions to the sea level estimates, both at global and at regional scale. This study is not a speculative exercise. The ICE-5G model adopted in this work is widely used in present day sea-level analysis, but discrepancies between the results obtained by different groups for the same ice models still exist, and it was the effort to set a common reference for the sea-level community that inspired this work. Understanding this issue is important to be able to reduce the artefacts introduced by a non-suitable ice model representation. This is especially important when developing new GIA models, since neglecting this problem can easily lead to wrong alignment of the ice and sea-level histories, particularly close to the deglaciation areas, like Antarctica.