A revised theory of POLAR WANDER during glacial isostatic adjustment & its consequences for THE SEA LEVEL ENIGMA

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The "Enigma"

20th century Sea Level Rise: 1.5 - 2.0 mm/yr
Steric part (thermal expansion): ~0.5 mm/yr
Leaving: ~1 mm/yr

The remaining ~1 mm/yr should be accounted for by contemporary ice melt, but glacial isostatic adjustment (GIA) models appear to preclude any such contribution!

The "sea level enigma" (Munk, 2002), describes how models of glacial isostatic adjustment (GIA) appear to completely reconcile a suite of rotation data, but in doing so rule out significant contemporary melting from global ice reservoirs. The "enigma" lies in ~1 mm/yr of 20th century sea level rise that remains unaccounted for.

Figure 1 shows a demonstration of the apparent reconciliation of three rotational data sets by model "GIA1," which has an upper mantle viscosity of 10^{21} Pa s and a lower mantle viscosity of 2×10^{21} Pa s. This "triple accord" rules out any significant contemporary melting from global ice reservoirs. Furthermore, even if the GIA models were tuned so that the J_2 and true polar wander (TPW) observations could accommodate sufficient present-day melting to explain tide gauge estimates, a consistency between the J_2 observation and the eclipse data (Munk, 2002) would require roughly the same amount of melting over the last several thousand years, in violation of geological sea level records (Fleming, et al., 1998)

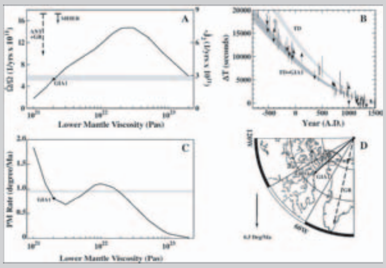

Figure 1

(A) Solid line—prediction of the GIA-induced present-day rate of change of the Earth's (normalized) axial rate of rotation, $\dot{\Omega}/\Omega$, or the degree two zonal harmonic of the Earth's geopotential, J_2, as a function of the lower mantle viscosity of the Earth model. The specific result generated from the model GIA1 is labeled. The shaded region represents a satellite-derived observational constraint (Nerem, et al., 1996). The vertical dashed arrows (labeled 'ANT+GR' and 'MEIER') are the predicted magnitudes of the signals associated with a net present-day melting of the Antarctic plus Greenland ice complexes equivalent to a eustatic sea-level rise of 1 mm/yr and Meier's (1984) tabulation of mountain glaciers and ice sheets (ESL=0.4 mm/yr), respectively.
(B) Vertical lines and represent the time difference, ΔT, between the occurrence of individual eclipses and the timing predicted on the basis of the Earth's current rotation rate (Stephenson, et al., 1995). The light-shaded region labeled 'TD' is the predicted time difference expected from tidal dissipation under the assumption that dissipation rates have remained fixed to present-day values. The dark shaded zone is the ΔT calculated by combining tidal deceleration with a predicted GIA-induced acceleration of the Earth's rotation, where the latter is based on model GIA1.
(C) Predictions of GIA-induced present-day polar wander speed as a function of lower-mantle viscosity based on the traditional ice-age rotation theory (Wu & Peltier, 1984). The shaded region encompasses observational constraints in two studies (McCarthy & Luzum, 1996; Gross & Vondrak, 1999) of astronomical records, and the prediction for model GIA1 is labeled.
(D) The observed (Gross & Vondrak, 1999) magnitude and direction of present-day secular polar wander (labeled 'OBS1'), as well as a prediction of the GIA signal based on traditional ice age rotation theory (Wu & Peltier, 1984) and the viscoelastic model GIA1. The dashed arrow labeled 'GR' represents the motion associated with a net present-day melting of the Greenland ice complex equivalent to a eustatic sea-level rise of 1 mm/yr. The vertical arrow at bottom left of the frame provides a magnitude scale.

A revised theory of Polar Wander

The response of the earth's rotation to changes in surface mass and topography feeds back upon surface deformation: the mass changes alter the Earth's inertia tensor, which shifts the rotational axis, which changes the centrifugal potential, which in turn forces and deforms the earth. The GIA-induced reorientation of the rotation vector is governed by a balance between the effects of the surface mass load, which acts to push the rotation pole away (or move the load toward the equator) and the stabilizing influence of the rotational bulge, which resists excursions of the pole from its initial state.

The rotational feedback depends critically on the "background" or initial oblateness of the unperturbed Earth. Previous studies have taken the initial state to be the hydrostatic form of the Earth under a centrifugal potential of spherical harmonic degree two. This introduces two errors: (1) the initial hydrostatic form incorrectly includes stress in the lithosphere, leading to reduced oblateness; and (2) there is no account of extra sources of oblateness such as convection-induced heterogeneity in mantle density.

We correct this (Mitrovica, et al. 2005) by considering the background hydrostatic form without lithospheric stress, and by augmenting the difference in the Earth's unperturbed polar and equatorial moments of inertia, C-A, by a small, observationally-inferred quantity δ (about 0.008): C-A becomes (C-A)(1+δ). The new treatment significantly reduces the rotational response to GIA processes (Figure 2), and therefore alters some conclusions based on true polar wander observations, including the "enigma" problem (Figure 3).

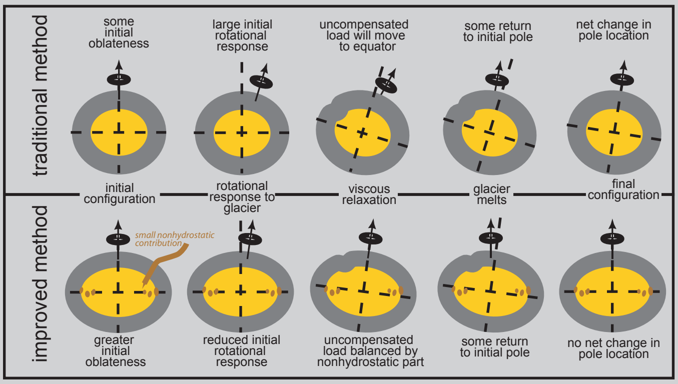

Figure 2
An illustration of the improved theory for calculating polar wander response to glacial loading. The traditional method (upper panel) has a smaller initial oblateness than the revised method (lower panel). The "blobs" in the mantle in the lower panel represent the extra nonhydrostatic component of the initial oblateness. The result is that the traditional method predicts greater polar wander than the improved theory.

Resolving the "Enigma"

A reanalysis of the sea level enigma is essential with the significant changes introduced by the improved theory of polar wander. Such a reanalysis may also be accompanied by improved observational values for the rotational data, including an updated observational constraint on true polar wander, labeled 'OBS2' in Figure 3, which references the secular polar motion to the hotspot reference frame, rather than the less stable 'mean lithosphere' frame (Gross & Vondrak, 1999). Also, an updated look at the J_2 secular trend (Benjamin, et al., 2006) shows it to depend on inconsistencies in the removal of the 18.6-year tide, which increases the uncertainty for this constraint (expressed in Figure 3 by the expanded range for the observed value for $\dot{\Omega}/\Omega$). A comparison of the revised predictions (solid lines) and updated observations are shown in Figure 3. We employ two new models, GIA2 and GIA3, defined by lower mantle viscosities of 2×10^{21} Pa s and 10^{23} Pa s, respectively (upper mantle remains 10^{21} Pa s). The predictions are generated by combining GIA calculations based on these models with the signal from a melting model 'MM' (see caption). Both scenarios provide a fit to the rotation observations which is as good as the GIA1 fit that defined the original sea-level enigma (Fig. 1).

Our reanalysis of space-geodetic, astronomical and archaeological constraints on Earth rotation has yielded a route to resolving the sea-level enigma. The GIA models we have considered are capable of simultaneously reconciling the suite of constraints on the Earth's rotational state in combination with an ongoing ice melting of order 1 mm/yr eustatic sea level.

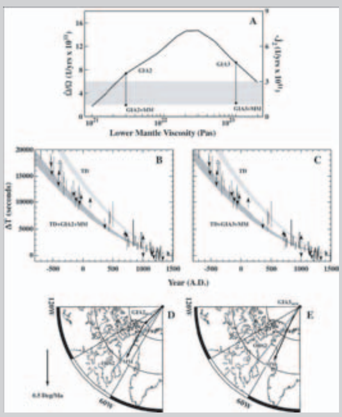

Figure 3

(A) As in Fig. 1A, a plot of GIA-induced J_2 and $\dot{\Omega}/\Omega$ as a function of lower mantle viscosity, with an updated observational constraint. GIA2 and GIA3 refer to results for Earth models with .LM=3×1021 Pa s and 1023 Pa s, respectively. Also shown is the net perturbation when the GIA predictions for these models are augmented by a signal from post-ice-age melting. This melt model (MM) is comprised of: (1) melting from mountain glaciers and small ice sheets (Meier, 1984). (ESL rise=0.4 mm/yr) and polar ice sheets (ESL=0.4 mm/yr) beginning in the 20th century; (2) Late Holocene melting of polar ice sheets (ESL=0.3 mm/yr). The signal associated with the latter is a function of the lower mantle viscosity (the former is not) and thus the MM signal is different for the GIA2 and GIA3 cases.
(B,C) As in Fig. 1B, except the results labeled 'TD+GIA2+MM' (frame B) and 'TD+GIA3+MM' (frame C) represent the total time shift, ΔT, predicted from tidal deceleration, and signals from both GIA and the melt history MM. The component of the MM model that involves the onset of melting in the 20th century has negligible effect on these predictions; however, the Late Holocene component of the MM loading (ESL=0.3 mm/yr) contributes a slowing of rotation that is a function of the adopted viscosity model.
(D,E) $GIA2_{new}$ (frame D) and $GIA3_{new}$ (frame E) are predictions of the GIA-induced present-day magnitude and direction of polar motion computed using the new rotation theory and viscoelastic models GIA2 and GIA3, respectively. In each frame, the vector MM represents the signal associated with the Late Holocene/20th century melt model defined above. In this case, the melting of polar ice sheets is either partitioned evenly between the south Greenland and Antarctic complexes (frames A-GIA2,B,D) or in the ratio 3:1 (A-GIA3, C,E).