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Rheological stratification of the lithosphere: A direct inference based upon the geodetically observed pattern of the glacial isostatic adjustment of the North American continent

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[1] A sequence of new analyses of the process of glacial isostatic adjustment (GIA) is described. The focus is upon the resolution of a recognized flaw in the currently prevalent model of this process, that denoted ICE-5G(VM2). The flaw concerns a previously noted inability of the model to simultaneously reconcile the VLBI and GPS measured rates of vertical and horizontal motion in the region of the North American continent that lay outboard and to the south of the Laurentide Ice-Sheet (LIS) at Last Glacial Maximum. This characteristic misfit of the model to the data has been suggested to be reconcilable only by recourse to models that explicitly incorporate the influence of lateral viscosity heterogeneity. It is demonstrated herein that, on the contrary, this flaw is entirely and unambiguously attributable to the rheological stratification of the lithosphere, an influence not previously accounted for in global models of the GIA process but which must exist on a priori grounds. **Citation:** Peltier, W. R., and R. Drummond (2008), Rheological stratification of the lithosphere: A direct inference based upon the geodetically observed pattern of the glacial isostatic adjustment of the North American continent, *Geophys. Res. Lett.*, *35*, L16314, doi:10.1029/2008GL034586.

1. Introduction

[2] The ICE-5G (VM2) model of the GIA process [*Peltier*, 2004] and its predecessor models ICE-4G (VM2) [*Peltier*, 1994,1996] and ICE-3G(VM1) [*Tushingham and Peltier*, 1991] constitute a sequence of increasingly accurate representations of this global phenomenon. The ICE-NG component of these models consists of a detailed space-time representation of the thickness histories of Late Pleistocene continental ice sheets, either for the time since Last Glacial Maximum at approximately 21,000 years before present (ICE-3G and ICE-4G) or for the entirety of the most recent 100 kyr glacial-interglacial cycle (ICE-5G). The most recent of these models has been especially successful as it has been shown to provide an excellent fit to the recently released Gravity Recovery and Climate Experiment (GRACE) time dependent gravity field observations [e.g., *Peltier*, 2007a; *Paulson et al.*, 2007] (and see below). In spite of the high quality of the fit that the model also delivers [*Peltier*, 2007b] to a dense globally distributed array of ^{14}C dated relative sea level histories, however, there exists a prominent anomaly first identified by *Argus et al.* [1999], and more recently re-confirmed by *Sella et al.* [2007]. This concerns the fact that, although the quality of the fit of the same model to rates of radial displacement at North American locations from which accurate measurements of rates of vertical motion of the crust are available is high, the misfit of the same model to observed horizontal motion observations is so large as to rule out the model entirely. As it happens this flaw in the model is attributable to the simplicity of the shallow visco-elastic structure that is characteristic of the VM2 spherically symmetric model. This is important from the perspective of global geodynamics as the existence of this misfit could, and has been, misconstrued to signal the importance of the influence of lateral heterogeneity of viscosity on the GIA process (e.g., as suggested recently by *Sella et al.* [2007]). Although this was also recognized as a possibility by *Argus et al.* [1999], it was left open by them as to whether a spherically symmetric model might be found that would provide a simpler explanation of the observed misfit. The purpose of this paper is to present such a refined model.

2. GIA Theory and Related Present Day Horizontal and Vertical Motions of the Crust

[3] The theory of the GIA process for Earth models with spherically symmetric internal visco-elastic stratification is embodied in the Sea Level Equation. This is an integral equation whose solution consists of a prediction of the manner in which the melt-water generated by continental de-glaciation must be distributed over the surface of the global ocean in order that this surface remain one of constant gravitational potential during the deformation of planetary shape that accompanies the GIA phenomenon. This integral equation, most recently reviewed by *Peltier* [2007b], takes the form:

$$S(\theta,\lambda,t) = C(\theta,\lambda,t)\left[\int_{-\infty}^{t} dt' \iint_{\Omega} d\Omega' \Big\{ L(\theta',\lambda',t')G^{L}_{\phi}(\phi,t-t') + \Psi^{R}(\theta',\lambda',t')G^{T}_{\phi}(\phi,t-t')\Big\} + \frac{\Delta\Phi(t)}{g}\right] \quad (1)$$

In (1) "S" is the longitude, latitude and time dependent relative level of the sea with respect to the deforming surface of the solid Earth, "C" is the time dependent ocean function which is unity over the oceans and zero over the continents, "L" is the space and time dependent thickness of grounded continental ice sheets, and "Ψ^R" is the change in the centrifugal potential due to the change in Earth's rotational state induced by the GIA process. "G^L_ϕ" and "G^T_ϕ" are Green functions which, when space-time

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convolved with the latter quantities, deliver predictions of the perturbation of the surface gravitational potential caused by these respective influences. The quantity "$\Delta\Phi(t)/g$" is a correction to the results obtained from the triple convolution integrals that is required in order to ensure that the mass of water that enters the global ocean is equal to that lost by the melting of land ice.

[4] For the purposes of the present paper we will be concerned not only with the relative sea level histories predicted by the direct solution of (1) but also with the associated vertical and horizontal motions of the crust, aspects of the response to the GIA process that are observable using the space geodetic techniques of VLBI and GPS. The general solutions for these elements of the response are expressible in the form [e.g., see *Peltier*, 2004]:

$$U(\theta,\lambda,t) = \sum_{l=0}^{\infty}\sum_{m=-l}^{+l}\left[\frac{4\pi a^3}{(2l+1)m_e}\left(L_{lm}h_l^{E,L} + \sum_{k=l}^{K(l)} q_k^l \beta_{lm}^k\right) + \frac{4\pi}{(2l+1)g}\left(T_{lm}h_l^{E,T} + \sum_{k=1}^{K(l)} q_k'^E \beta'^K_{lm}\right)\right] Y_{lm} \tag{2a}$$

$$V(\theta,\lambda,t) = \sum_{l=0}^{\infty}\sum_{m=-l}^{+l}\left[\frac{4\pi a^3}{(2l+1)m_e}\left(L_{lm}l_l^{E,L} + \sum_{k=l}^{K(l)} t_k^l \beta_{lm}^k\right) + \frac{4\pi}{(2l+1)g}\left(T_{lm}l_l^{E,T} + \sum_{k=1}^{K(l)} t_k'^E \beta'^K_{lm}\right)\right] \nabla Y_{lm} \tag{2b}$$

In (2a) "U" is the scalar radial displacement and in (2b) "V" is the vector tangential displacement [see *Peltier*, 1998]. The Y_{lm} are the usual vector spherical harmonics, "∇" is the tangential gradient operator, "a" and m_e are the Earth's radius and mass respectively, the L_{lm} are time dependent spherical harmonic coefficients of the surface mass load and T_{lm} those of the changing centrifugal potential. The $h_l^{E,L}$ and $l_l^{E,L}$ are the elastic asymptotes of the radial and tangential displacement Love numbers [*Peltier*, 1974]. The theoretical solutions are completed by the definitions of the β parameters as [see, e.g., *Wu and Peltier*, 1982]:

$$\beta_{lm}^k = \int_{-\infty}^{t} L_{lm}(t)e^{-s_k^l(t-t')}dt', \tag{3a}$$

$$\beta'^k_{lm} = \int_{-\infty}^{t} T_{lm}(t)e^{-s_k^l(t-t')}dt' \tag{3b}$$

For the remainder of this paper the focus will be upon the application of the theoretical results embodied in equations (1)–(3) to the understanding of the detailed characteristics of the GIA process in North America.

3. Two Models of the Internal Visco-elastic Stratification: The "Double Lithosphere"

[5] Figure 1a of this paper compares the VM2 model of the radial viscosity structure of the planetary interior [*Peltier*, 1996] to a new model that will be referred to in what follows as VM5, the latter being a 5-layer approximation to VM2. The only significant difference between these models is that, whereas VM2 has a perfectly elastic

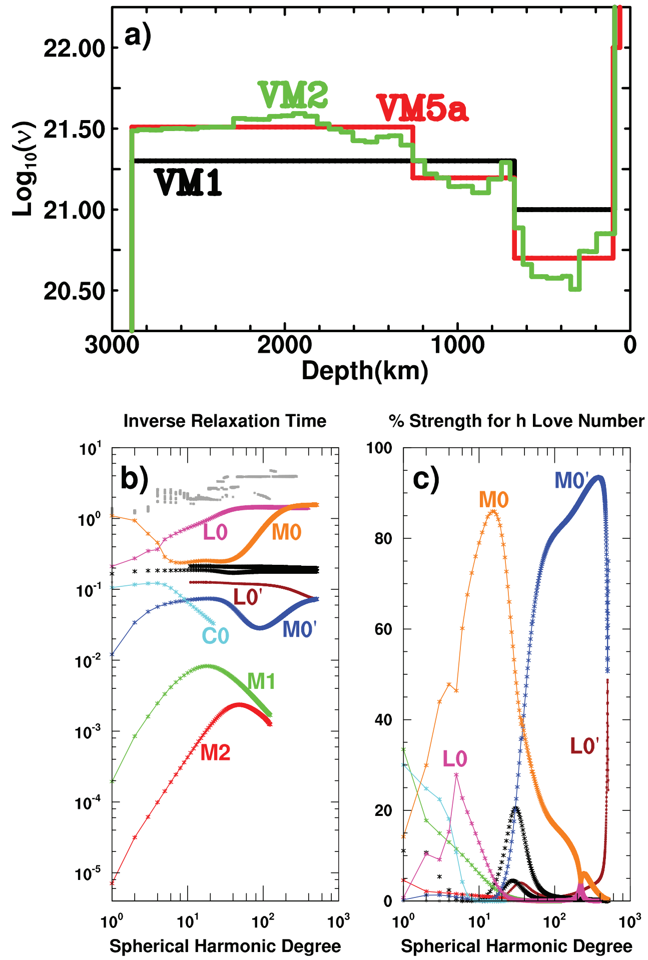

Figure 1. (a) Comparison of the three viscosity models VM1, VM2 and the new model VM5 which is of interest here. VM2 is the model originally inferred on the basis of a Bayesian inversion of all of the available GIA data that could be invoked to constrain the radial profile of mantle viscosity. The VM1 model is that employed as a first guess in the inversion procedure. VM5 is the new model that is a best fit 5 layer model to the VM2 structure, one that differs significantly from this original structure only by the insertion of an additional 40 km thick layer of viscosity equal to 10^{22} Pas below the 60 km thick elastic lithosphere. This lower lithospheric layer defines the transition between the elastic lithosphere and the upper mantle and transition zone within which the viscosity is taken to be equal to 5 × 10^{21} Pas. (b) The relaxation diagram for the VM5 model which shows inverse relaxation time for each of the individual modes of viscous-gravitational relaxation as a function of spherical harmonic degree. The unit of time on the basis of which the non-dimensional relaxation time is presented is 1000 years. (c) The fractional strength of each of the individual modes of viscous gravitational relaxation color coded to the modal branches in Figure 1b.

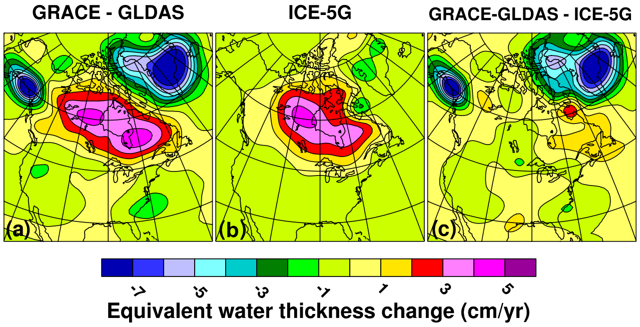

Figure 2. Comparison of predictions of the time dependence of the gravitational field of the planet using the ICE-5G (VM2) model and the same field observed by the GRACE satellites. The comparison is made based upon the assumption that the degree 2 and order 1 Stokes coefficients may be neglected.

lithosphere of thickness 90 km, VM5 includes a 60 km thick perfectly elastic layer at the Earth's surface beneath which there exists a 40 km thick layer with viscosity equal to 10^{22} Pa s. Such additional structure in the near surface rheological stratification might be expected to strongly influence the tangential stress to which the overlying elastic layer is subject through its ability to relax the stress field within it as the rebound process proceeds. Clearly the intention with VM5 is to incorporate the influence of radial viscoelastic stratification of the near surface lithosphere, an entirely expected characteristic that must exist because of the increase of temperature with depth and the fact that the creep resistance of a solid decreases exponentially with increasing temperature. Variants upon this illustrative structure are equally compatible with the data, both in regards to the thickness of the elastic surface layer and in regards to the number and specific viscosities of the layers that are introduced to define the stratification. This non-uniqueness will be more fully explored elsewhere as our interest here is simply to establish the profound influence that such stratification exerts upon the horizontal velocity field. Figure 1b illustrates the relaxation diagram for this model which consists of a plot of the inverse relaxation times of the modes of viscous-gravitational relaxation that govern the GIA process as a function of spherical harmonic degree. These modes are counted by the letter "K" in equations (2a) and (2b). Figure 1c shows the amplitude of each of these modes in a color coded format that is keyed to the similarly color coded branches of the relaxation diagram. Modal amplitudes are shown as the percent strength that each mode contributes to the viscous relaxation at each spherical harmonic degree. Inspection of the relaxation diagram in Figure 1b in comparison with that for the original VM2 model [e.g., see *Peltier*, 2004, Figure 2] demonstrates that for the new model, the original M0 and L0 fundamental modes of the mantle and lithosphere are "doubled" at short wavelength (high degree) the relaxation spectrum in that two new branches denoted M0′ and L0′ of identical form appear. The introduction of the thin layer of high but finite viscosity beneath the perfectly elastic lithosphere therefore adds additional structure to the relaxation diagram for the

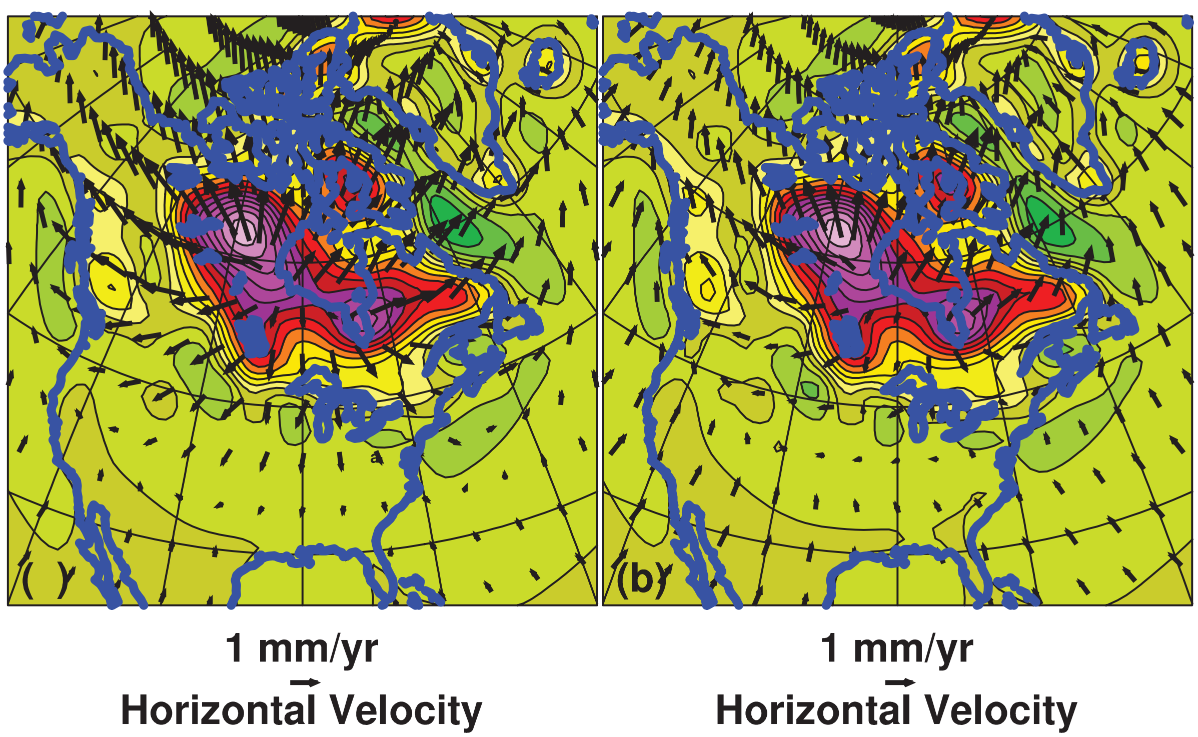

Figure 3. Overlay of predictions of the vertical and horizontal rates of motion of the crust of the solid Earth predicted by the (a) ICE-5G(VM2) and (b) ICE-5G (VM5) models. Notable is the fact that the only significant difference in the predictions of the two models are for horizontal motion south of the ice covered region.

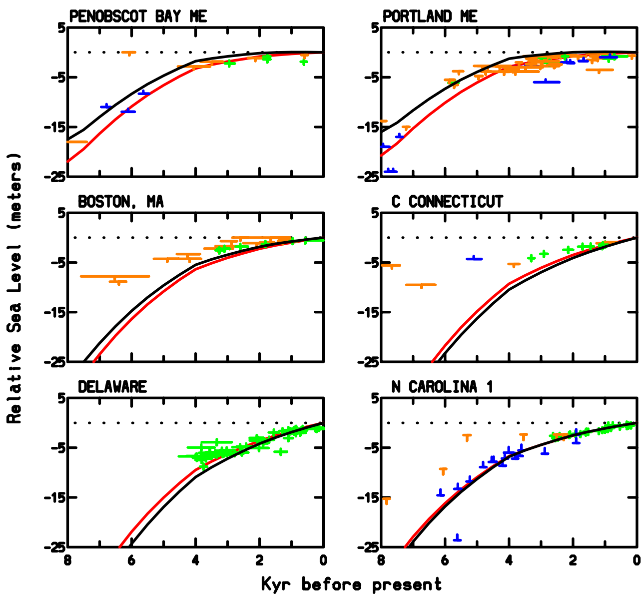

Figure 4. Examples of relative sea level history predictions for 6 locations along the northern portion of the east coast of the North American continent. This is the region in which the differences in the predictions between the VM2 and VM5 models are largest. The red curves are for the parent ICE-5G (VM2) model whereas the black curves are for the new ICE-5G (VM5) model introduced in this paper. The differences in these predictions are of no significant consequence given the error bars on the data.

(short) horizontal length scales sensitive to the presence of this near surface structure. Our interest is in the differential impact that this feature will have upon vertical as compared to horizontal motions.

4. Importance of Rheological Stratification of the Lithosphere

[6] Since the response to the GIA process depends equally upon the model employed to represent the history of surface mass load variations and the model of the internal viscoelastic stratification of the planet, it will be important to first establish the quality of the parent ICE-5G (VM2) model that is to be perturbed by the replacement of VM2 by VM5. This is established by Figure 2 in which we compare the prediction of the ICE-5G (VM2) model of the time dependent gravity field of the planet over the North American landmass to that represented by a recent release (RL04) of the GRACE satellite observations (see http://podaac.jpl.nasa.gov/grace/data access.html). The raw GRACE data have been reduced using standard procedures in which an annual cycle and its first harmonic as well as a harmonic component of 161 day period are first fit to each Stokes coefficient of each of the monthly data sets together with a constant bias and a constant secular rate of change. The correlation of errors across adjacent spherical harmonic orders is reduced by applying the correlated error filter proposed by *Swenson and Wahr* [2006] and a Gaussian smoothing of the field thereafter is also applied with a half-width of 300 km. Prior to comparison with the GIA prediction, the influence of changing surface hydrology is removed by application of the model of *Rodell et al.* [2004]. Figure 2a shows the GRACE observations, so corrected, as the time rate of change of the thickness of an equivalent layer of water at the Earth's surface. In Figure 2b the GIA prediction of the ICE-5G (VM2) model is presented in the same format. Figure 2c shows the difference between these fields, demonstrating that the theory fits the primary anomaly in the observed field over Canada quite accurately since the subtraction eliminates this primary anomaly almost entirely. The minor misfits that exist over this region are such as to suggest the need for small corrections to the ice load to the east of James Bay The significant residual anomalies that remain over Greenland and Alaska are due to the ongoing loss of land ice in these regions due to greenhouse gas induced warming of the lower atmosphere (e.g., see *Velicogna and Wahr* [2005, 2006] for discussion). These results demonstrate that the original ICE-5G (VM2) model, which was published prior to the availability of the GRACE observations, is of high quality.

[7] Figures 3a and 3b present the most important result of this paper. Figures 3a and 3b show overlays of the predicted present day rate of vertical motion of the crust and the present day rate and direction of horizontal motion of the crust for the models ICE-5G (VM2) and ICE-5G (VM5) respectively. It will be noted by inspection of Figures 3a and 3b that the impact of the introduction of the rheological stratification of the lithosphere into the model has no significant effect upon the predicted rates of vertical motion. However, the predicted rates of horizontal motion are fundamentally modified by the incorporation of the viscous transition layer beneath its near surface elastic counterpart. This transformation is so fundamental that the horizontal velocity field outboard and to the south of the Laurentide ice sheet over the entire US land mass is rendered incoherent and of very low amplitude in the ICE-5G (VM5) model. In its ICE-5G (VM2) counterpart, however, this signal is predicted to consist of a highly coherent outward motion of amplitude in excess of 1 mm/yr that extends as far south as Florida. Comparison of the results in Figure 3b with the equivalent results given by *Sella et al.* [2007, Figure 1] will demonstrate that the new model fully reconciles the misfit upon which their paper has focused, a misfit first identified in the paper of *Argus et al.* [1999].

[8] It is very important to understand that this reconciliation of the present day vertical and horizontal motion predictions of the model is accomplished without damaging in any significant way the quality of the fits to radio-carbon dated relative sea level histories from sites along the east coast of the US, a region in which it has been previously demonstrated that the model possessed considerable skill. The relative insensitivity of relative sea level predictions to the presence or absence of lithospheric stratification is demonstrated in Figure 4 on which complete Holocene history predictions for 6 sites from US east coast locations are compared for the 2 models. At northern locations the sea level history predictions of the VM5 based model lie slightly above those of VM2 whereas at southern locations the reverse is true. At sufficiently southern locations there is no difference in the sea level predictions of the two models at all. The observational errors on the observed rsl histories

are such that the data may be unable to discriminate between the two models of the radial viscoelastic structure.

5. Conclusions

[9] A previously noted flaw in the ICE-5G (VM2) model of the GIA process identified by *Argus et al.* [1999] and confirmed by *Sella et al.* [2007] has been shown to be entirely eliminated simply by the introduction of viscoelastic stratification of the near surface lithosphere. The very slow horizontal motion that is observed to occur in the region to the south of the Laurentide Ice Sheet is due to the fact that the stresses in the region beneath the elastic surface lithosphere are able to relax significantly during the course of the rebound process. That such a transition between the relatively low viscosity of the asthenosphere and upper mantle and the elastic surface layer should exist is an inevitable consequence of the temperature dependence of the creep resistance.

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