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Glacial isostasy and plate motion

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Abstract

The influence of glacial-isostatic adjustment (GIA) on the motion of tectonic plates is usually neglected. Employing a recently developed numerical approach, we examine the effect of glacial loading on the motion of the Earth's tectonic plates where we consider an elastic lithosphere of laterally variable strength and the plates loosely connected by low viscous zones. The aim of this paper is to elucidate the physical processes which control the GIA induced horizontal motion and to assess the impact of finite plate-boundary zones. We show that the present-day motion of tectonic plates induced by GIA is at, or above, the order of accuracy of the plate motions determined by very precise GPS observations. Therefore, its contribution should be considered when interpreting the mechanism controlling plate motion.

Key words: Glacial-isostatic adjustment, tectonic-plate motion, surface motion, plate boundaries, lithosphere, ITRF 2005

PACS: 91.50.Kx, 91.45.Ga, 91.45.dk, 91.45.dc, 91.55.Ln, 91.10.Fc

1. Introduction

Glacial isostatic adjustment (GIA) describes the ongoing readjustment of the Earth arising from the quasi-periodic mass redistribution between continental glaciers, ice sheets and the ocean during glacial cycles, of about 100 kyr in periodicity (Petit et al., 1999). The fluctuation in global ice coverage during the last glaciation, extending over wide areas of North America, northern Europe and Antarctica, involved changes in ice-thicknesses of up to 4 km (Denton and Hughes, 1981; Tarasov and Peltier, 2004), with sea level in many areas being over 100 m below the present level (Fleming et al., 1998), causing large deformations that remain active and detectable by modern geodetic techniques (Lambert et al., 2001; Pagiatakis and Salib, 2003). Therefore, the ongoing GIA is usually taken into account when interpreting, for example, present-day secular trends in the Earth's gravity

field and rotation axis, and long-term variations in sea level. GIA-induced horizontal motion inferred by space geodetic techniques has primarily been used in studies dealing with formerly glaciated regions such as Scandinavia or North America (James and Morgan, 1990; Milne et al., 2001; Sella et al., 2007). However, the present-day accuracy of such techniques and improved modelling of GIA enables us to study the induced horizontal motion globally and to assess its effect on the motion of all of the Earth's major tectonic plates.

The motion of the plates is predominantly driven by convective processes in the Earth's mantle with characteristic timescales of 1–100 Myr (Knopoff, 1964; Richter, 1973; McKenzie et al., 1974). There are two principal approaches for quantifying plate velocities: Geologically-based models like NUVEL-1A (DeMets et al., 1994), that rely on the analysis of geomagnetic reversals and other geological and seismic data, represent plate velocities averaged

over the last million years. In contrast, geodetically-based models like REVEL (Sella et al., 2002) rely on the analysis of Global Positioning System (GPS) observations. The latter represent plate velocities averaged over the last decade and a half (A.D. 1993–2008). The GIA process, with a period of 0.1 Myr, therefore, represents an undetectable transient perturbation of the geologically-inferred model, but a detectable component in the geodetically-inferred secular trends used to construct the model. The usual way to eliminate the GIA-induced horizontal motion from GPS observations is to exclude those GPS observations that are recorded in areas near formerly glaciated regions (Sella et al., 2002). The argument for such a procedure is that the GIA-induced horizontal displacements are about one order of magnitude smaller than the associated vertical displacements and are concentrated to the formerly glaciated regions (Peltier et al., 1986; Lambert et al., 2001). This approach does not, however, remove the effect of GIA from GPS observations completely, since GIA-induced horizontal motion is distributed over the entire globe with amplitudes of the order of one mm/yr (James and Morgan, 1990; Wang and Wu, 2006b). Since the plate velocities are of the order of a few cm/yr, the GIA-induced horizontal motion generally contributes less than 10 % of the total observed signal (Sella et al., 2002). Despite such a small amplitude, this signal is present in the extremely precise continuous tracking data of GPS (Calais et al., 2006).

GIA induced horizontal motions are much more sensitive to mechanical properties that lie above the mantle, and, as a consequence, to lateral variations in lithosphere strength, than are the GIA-induced vertical motions. Due to computational rigor inherent to the modelling of viscoelastic lateral heterogeneities, various approximations, such as introducing some symmetries like a 2-D structure for a half-space model (Sabadini et al., 1986; Kaufmann et al., 1997) or axial symmetry for a spherical earth model (e.g. Wu and van der Wal, 2003; Martinec and Wolf, 2005; Klemann et al., 2007) have been employed in past work. Half-space models that consider structural features in 3-D are constrained to regional GIA due to the neglect of sphericity: Europe (Marotta and Sabadini, 2004; Kaufmann and Wu, 1998, 2002; Steffen et al., 2006) Laurentia (Wu, 2005) and Antarctica (Kaufmann et al., 2005).

More recently, global approaches use spherical finite element models with a grid strategy that incorporates lateral variations in mantle viscosity and

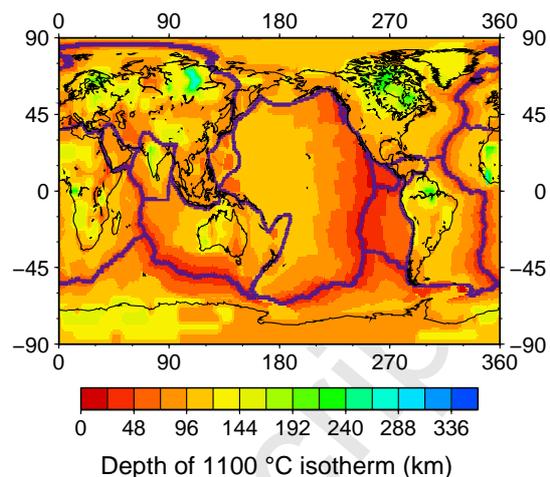


Fig. 1. Mosaic of elastic lithosphere thickness defined by the depth of the 1100 °C isotherm inferred from the thermal structure of continental lithosphere (Artemieva, 2006) and age structure of oceanic lithosphere (Müller et al., 1997). Plate boundaries (purple lines) are approximated by 200 km wide zones with the same viscosity as the upper-mantle.

lithospheric strengths (Wang and Wu, 2006b,a) or plate boundaries (Latychev et al., 2005; Whitehouse et al., 2006). Predictions from such models form a more realistic basis for comparison to the observed global horizontal motions. In this study, we specifically demonstrate the importance of plate boundaries on the GIA-induced horizontal motion and, therefore, better decipher how GIA places an imprint on observed plate-tectonic motion.

2. Modelling of GIA-induced motion

To examine how the GIA process effects plate motion, we approximate the Earth by a self-gravitating sphere with a linear viscoelastic rheology. The upper and lower mantles have uniform viscosities of 5×10^{20} Pa s and 10^{22} Pa s, respectively; the model accommodates a fluid core. The elastic part of viscoelastic rheology is considered incompressible with the elastic shear modulus and mass-density defined by the Preliminary Reference Earth Model. The spectral finite element method developed by Martinec (2000) is applied which allows strong lateral viscosity contrasts to be considered, including lateral variations in lithosphere thickness. The resolution in horizontal directions is represented by spherical harmonics up to degree 170 which corresponds to a spatial resolution of about 120 km, and vertically by finite elements of 5 km in the lithosphere and upper mantle.

We define the base of the elastic lithosphere to be at the depth of the 1100 °C isotherm (Figure 1), assuming to be the characteristic temperature below which the Earth’s material is dominated by elasticity for strains having time scales shorter than 0.1 Myr. The thickness of continental lithosphere is directly derived from a global thermal model, where we used the temperature profiles on a $5^\circ \times 5^\circ$ grid provided by Artemieva (2006). The thermal structure of the oceanic lithosphere is derived from its age (Müller et al., 1997) by applying a simple plate-cooling model. The 1100 °C isotherm is calculated by assuming heat conduction inside the oceanic plate between the mantle of 1300 °C and surface of 0 °C (e.g. Turcotte and Schubert, 2002, p. 161). In order to consider the role of plate boundaries in the decoupling of shear stresses between the plates, the main plate boundaries taken from Bird (2003) are approximated as 200-km narrow zones of viscoelastic material, and further approximated assuming the same viscosity as the upper mantle (Figure 1).

The surface loading applied considers the main areas of glaciation (Laurentide, Greenland, Fennoscandia and Antarctica) over the last glacial cycle. The spatio-temporal evolution of the Laurentide and Greenland ice sheets are described by the standard ICE3G model (Tushingham and Peltier, 1991) for Laurentia, the Fennoscandian ice sheet by the SCAN model (Lambeck et al., 1998), and the Antarctic ice sheet by the ICE3G model. This model gives a global sea-level fall of -105 m at the Last Glacial Maximum (LGM) (Hagedoorn et al., 2006). The mass conservation principle is applied for water exchange between ocean and ice sheets during the Pleistocene glaciation where, for simplicity, we uniformly reduced the sea-level in accord with continental ice volume change assuming fixed coast lines.

3. Influence of tectonic plates on GIA-induced motion

The spatio-temporal changes in surface-mass load during the Pleistocene glaciation induce vertical mantle-material flow resulting in present-day surface-uplift rates of up to 20 mm/yr. This material flow is accompanied by horizontal material transport inside the mantle (James and Morgan, 1990). Since the viscosity of the upper mantle is significantly lower than that of the lower mantle, the

horizontal flow is concentrated in the layer between a highly viscous lower mantle (below 670 km depth) and the elastic lithosphere.

Figure 2 shows the horizontal and vertical present-day velocities induced by the assumed late-Pleistocene glaciation cycle. The present-day GIA-induced horizontal flow displays a hemispheric pattern and, generally, the geometry of this flow means that it orients toward the areas of present-day uplift. The flow of the northern hemisphere is induced by the formerly glaciated regions of Fennoscandia, Greenland and Laurentia and is directed northward, while the flow of the southern hemisphere, induced by the glaciation of Antarctica is directed southward (e.g. Wang and Wu, 2006b). Furthermore, abrupt changes in the horizontal velocities appear at several plate boundaries, for example at the boundary between the Pacific and North American plates, the Indian and Antarctic plates and between the Australian and Antarctic plates (Figure 2, right). These features do not appear if a model with a uniform lithosphere thickness of 100 km is assumed (Figure 2, left).

More striking is to consider the spatial gradient of the displacement rate, $\nabla \dot{\mathbf{u}}$. Regarding the strain rate, $\dot{\epsilon}$, we show in Figure 3 the divergence of the surface components and its second invariant:

$$\text{div}_h \dot{\mathbf{u}} = \dot{\epsilon}_{\theta\theta} + \dot{\epsilon}_{\phi\phi}, \quad (1)$$

$$\dot{\epsilon}_{h,II} = \sqrt{\dot{\epsilon}_{\theta\theta}^2 + \dot{\epsilon}_{\phi\phi}^2 + 2\dot{\epsilon}_{\theta\phi}^2}. \quad (2)$$

Regarding the vorticity, $\boldsymbol{\omega}$, it is important to monitor its radial component and its absolute value:

$$\omega_r = \mathbf{e}_r \cdot (\nabla \times \dot{\mathbf{u}}), \quad (3)$$

$$\omega = |\nabla \times \dot{\mathbf{u}}|. \quad (4)$$

Apart from the last quantity, wherein radial gradients are also involved, the quantities (Eqs. 1–3) are defined by the surface components of the displacement field. First, it should be mentioned that positive divergence means dilation, whereas negative divergence means compression of the surface plane. For the radial vorticity, a negative sign indicates a dextral rotation of an idealized surface element whereas a positive sign indicates a sinistral rotation. The other two components are positive by definition. The divergence shows the known features of dilation of the formerly glaciated regions which are surrounded by areas of compression as direct consequence of the uplift pattern. In addition, the plate boundaries around Antarctica mainly show di-

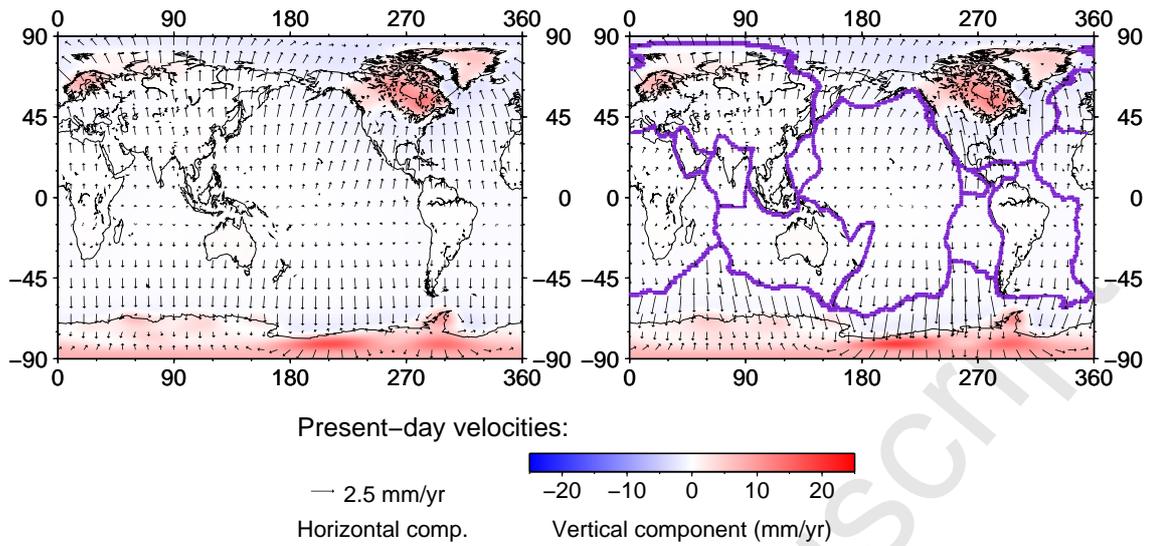


Fig. 2. Prediction of present-day surface velocities induced by the last glacial cycle with a laterally homogeneous lithosphere structure (left) and the considered 3-D earth model (right). Purple areas denote the considered plate boundaries.

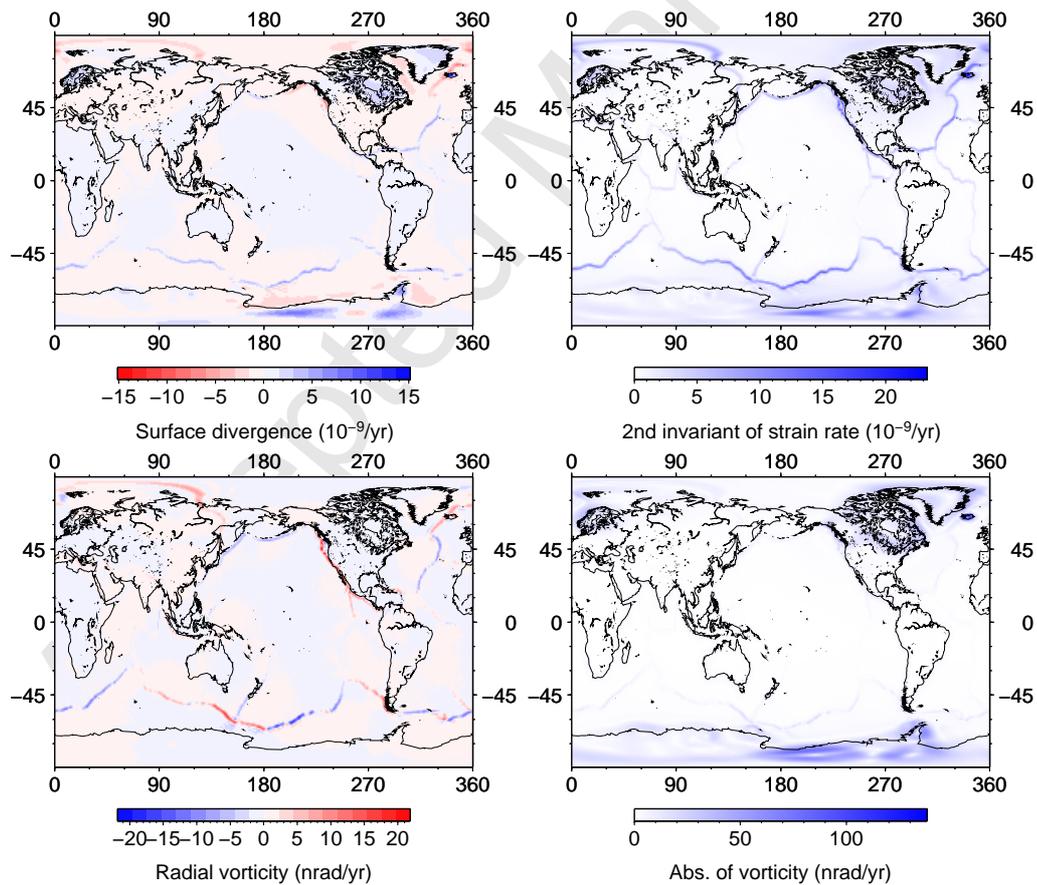


Fig. 3. Spatial surface fields related to the deformation rate according to (1)–(4): divergence in surface plane, second invariant of surface strain rate, radial component of rotation rate and absolute value of rotation rate.

lation whereas the Mid-Atlantic ridge and the Arctic Lomonosov ridge show compression.

The second invariant of the surface strain rate shows a similar pattern like the divergence, only the plate boundaries are more pronounced in this plot. In comparison to the values inferred for plate tectonic motion exceeding thousands of $10^{-9}/\text{yr}$ Kreemer et al. (2003), the GIA contribution represents a small perturbation. The radial vorticity directly resembles the toroidal motion, which does not appear for a 1-D earth model. Such a model if loaded by a surface pressure will only experience spheroidal motions and, therefore, the radial vorticity is zero. Here, the largest amplitudes appear at the plate boundaries while vorticity in the regions of large uplift are negligible. The total vorticity is almost a factor of 10 larger than the radial component alone, as it collects information pertaining to all components of the deformation-rate tensor including the tilting of the surface, which tends to follow the migrating peripheral bulge (James and Bent, 1994). Therefore, the largest amplitudes surround the former glacial maxima, where the strongest uplift gradients appear (compare Figure 2). This feature is generally common to all GIA models, appearing in the 1-D earth model as well. The plate boundaries showing gradients in horizontal motion are diminished.

The degree variance spectra shown in Figure 4 provide insight into the partitioning of surface motion between the spheroidal and toroidal component (e.g. Forte and Peltier, 1987). Shown are the degree variances

$$\sigma_U^2(l) = \sum_{m=0}^l U_{lm} U_{lm}^* \quad (5)$$

$$\sigma_V^2(l) = \sum_{m=0}^l V_{lm} V_{lm}^* \quad (6)$$

$$\sigma_W^2(l) = \sum_{m=0}^l W_{lm} W_{lm}^* \quad (7)$$

of the vertical and horizontal spheroidal component, U_{lm} , V_{lm} , and the toroidal component, W_{lm} , of the velocity field at the surface as function of Legendre degree, l , and order m (see Eq. A.1). Asterix, $*$, denotes the conjugate complex. Proportional to these quantities are the surface divergence and radial vorticity which are scaled by $l(l+1)/R$ with respect to V_{lm} and W_{lm} (e.g. Čadež and Ricard, 1992). The variances show that the toroidal motion reaches the amplitude of the spheroidal V component for $l \geq 5$.

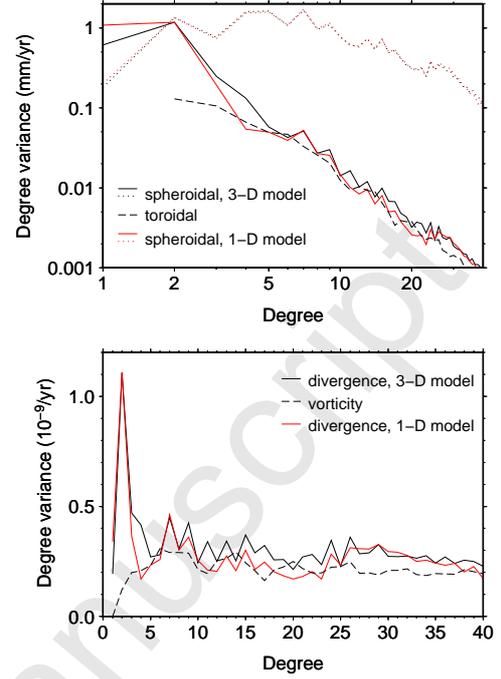


Fig. 4. Degree variance spectra of spheroidal and toroidal surface motion (left) and the derived quantities of surface divergence and radial vorticity (right). The spheroidal velocities are splitted into its horizontal contribution (solid lines) and its radial contribution (dotted lines).

An equipartitioning of kinetic energy also appears in the motion of the tectonic plates (e.g. Hager and O'Connell, 1978; Čadež and Ricard, 1992; Bercovici, 1995) where, due to the existence of lithospheric plates the efficiency of convection as a poloidal motion is enhanced by reducing the overall dissipation in the system (Bercovici, 2003). Here, the equipartitioning gains strength at degrees larger than 3, whereas for longer wavelengths the spheroidal motion dominates. An exposition on this topic is beyond the scope of this paper, but the controlling mechanics are likely to have strong analogies to the convective systems described by Bercovici (2003). The vertical motion, dotted lines, is dominated by buoyant forces that cause uplift in the previously glaciated areas and does not noticeably change if we consider lateral lithospheric variations. This is also shown in Figure 2 where no broad scale variations in the uplift process are predicted.

In order to better understand the dynamics appearing in these numerical solutions, the material flow pattern along a cross-section passing through the main areas of former/current glaciation in the northern hemisphere is shown in Figure 5. The

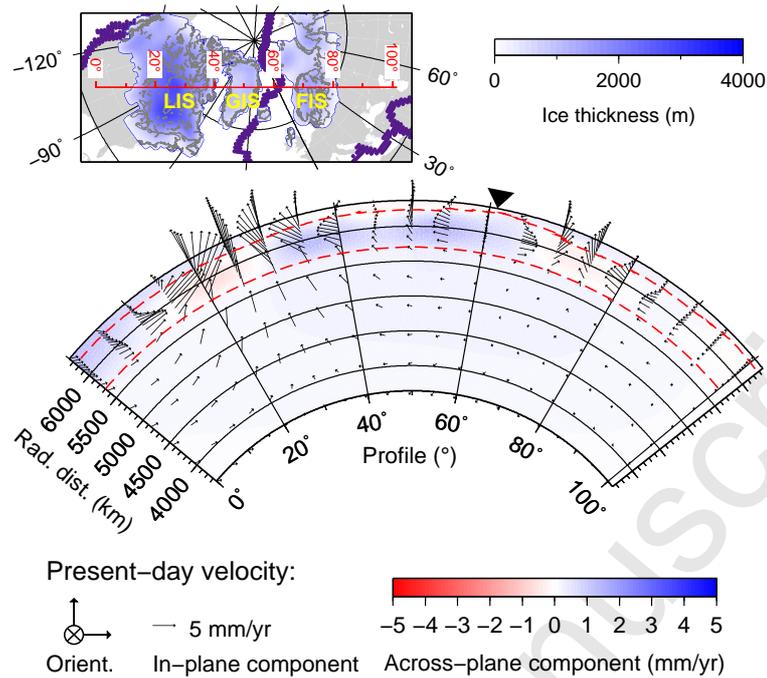


Fig. 5. Present-day GIA-induced velocities along a cross-section passing through areas that contain the Laurentide (LIS), Greenland (GIS) and Fennoscandian (FIS) ice sheets, respectively. The upper panel shows the ice-sheet extent (blue line) and thickness at the last glacial maximum relative to present day. The profile of the cross section is marked in red. The plate boundaries are plotted in purple. The lower panel shows the present-day GIA-induced velocities in the plane of the cross section (vectors) and perpendicular to the plane (blue indicates a flow directed into the plane). The inverted triangle denotes the position of the mid-Atlantic ridge, dashed red lines denote the base of the effective elastic lithosphere and the boundary between upper and lower mantle.

lateral flow shown in the upper panels is mainly confined to the upper mantle and flow in the lower mantle is only visible below Laurentia, a feature which confirms the fact that the regional GIA is additionally affected by the lower mantle (Wolf et al., 2006) whereas for Fennoscandia motion is, relatively, confined to upper mantle processes (Wieczerkowski et al., 1999; Martinec and Wolf, 2005). The lateral mantle-material flow manifests a shear traction on the overlying plates. The traction, consequently, pulls the tectonic plates toward the former glaciation centres of Laurentia, Greenland and Fennoscandia. The role of the mid-Atlantic ridge as a soft plate boundary is complex because ongoing GIA is occurring on both sides of the cross-section. Figure 6 more closely examines the upper mantle for the same profile. In the right panel of Figure 6 the flow pattern for a 1-D earth model is shown for comparison. Although the flow shown in the upper panels of Figure 6 are similar (which corresponds to the similar flow around the previously glaciated regions at the surface, see Figure 2), it is evident that the lateral flow pattern tracks the viscous portion

of the upper mantle and is strikingly discontinuous at the lithospheric base. The discontinuity in the motion becomes more evident in the vorticity (Figure 6, lower panels), as the intensity of the parameter makes a step-like change across the rheological boundaries. So, the vector component normal to the plane (off-plane) describes the rotation of idealized rigid particles in the plane, sinistral in red and dextral in blue. The vertical component of the vector shown here describes the radial vorticity as in Figure 2 and the horizontal in-plane component exhibits a tilting of the particle out of the plane. For the 1-D earth model it is evident that within the earth radial vorticity is absent. Again, recall that this component is solely described by a toroidal field. The pattern of the horizontal components for the two models are similar in this portion of the spherical earth, especially in the lithosphere. The amplitude of vorticity is largest near the boundaries of the upper mantle, whereas they are almost constant inside the elastic lithosphere, a consequence of near-unidirectional motion in the lithosphere. Due to the direction of the profile normal to the load

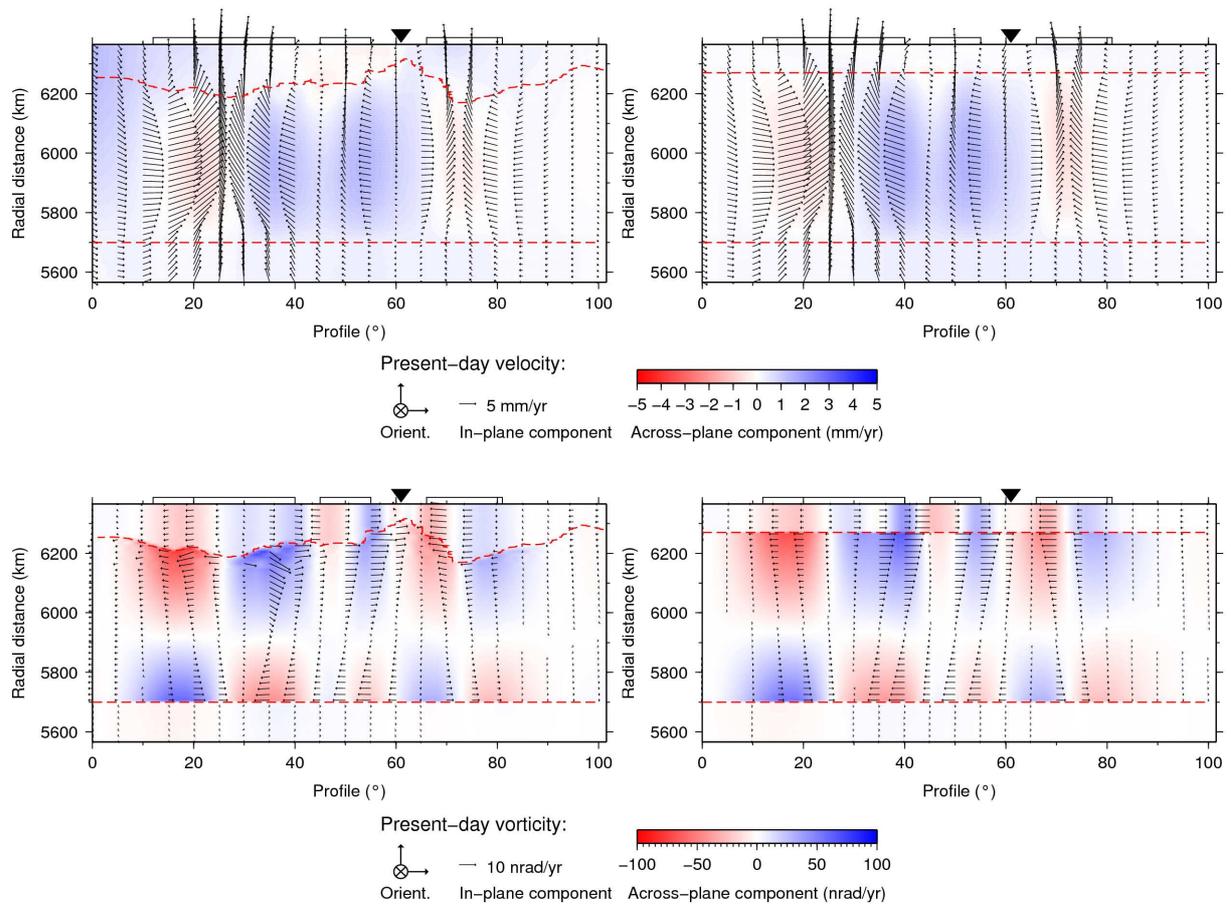


Fig. 6. Present day velocity (upper panels) and vorticity (lower panels) on profile I over a limited mantle/lithosphere range. Fields for a 1-D earth model with 100 km lithosphere thickness are presented on the right. The red lines indicate the top and base of the viscoelastic upper mantle. At the top, the inverted triangle shows the position of the mid-Atlantic ridge and the rectangulars the extension of the glacial loads at LGM.

margins, the in-plane components of vorticity are quite small in comparison to the normal component. Inside the lithosphere, the normal component of rotation resembles the tilting of the surface according to the uplift gradient with distance from the former centres of glaciation. The rotation is sinistral to the right and dextral to the left of the respective uplift centres. The horizontal in-plane component is one order of magnitude smaller than the off-plane component. The vertical component, ω_r , becomes evident in the upper mantle where the lithosphere base shows a significant slope, e.g. at 35° on the profile. Here, ω_r is also comparable to the horizontal in-plane components and the discontinuity in the off-plane component across the lithospheric base is also evident.

In order to resolve the effect of a low-viscosity plate boundary on the GIA-induced flow, we choose

a second cross-section (Figure 7) that passes through the Southeast-Indian ridge between the Australian and Antarctic plates. For this cross section it is striking that the GIA-induced horizontal velocities are relatively subdued north of the Southeast-Indian ridge and abruptly promoted south of the ridge. In the vicinity of the ridge, the sub-surface horizontal velocities increase toward the surface, approximating the behaviour of material flow for the case of a free-slip boundary condition. The amplitude of the horizontal-velocity contrast is 2 mm/yr (Figure 8). Although this is only a small part of the observed 70 mm/yr spreading rate of this ridge, the presence of the ridge significantly changes the material flow pattern in comparison to the case without a plate boundary (Figure 8, bottom panel). Traversing across the Southeast-Indian ridge, the abrupt change in horizontal velocity is predicted in the 3-D

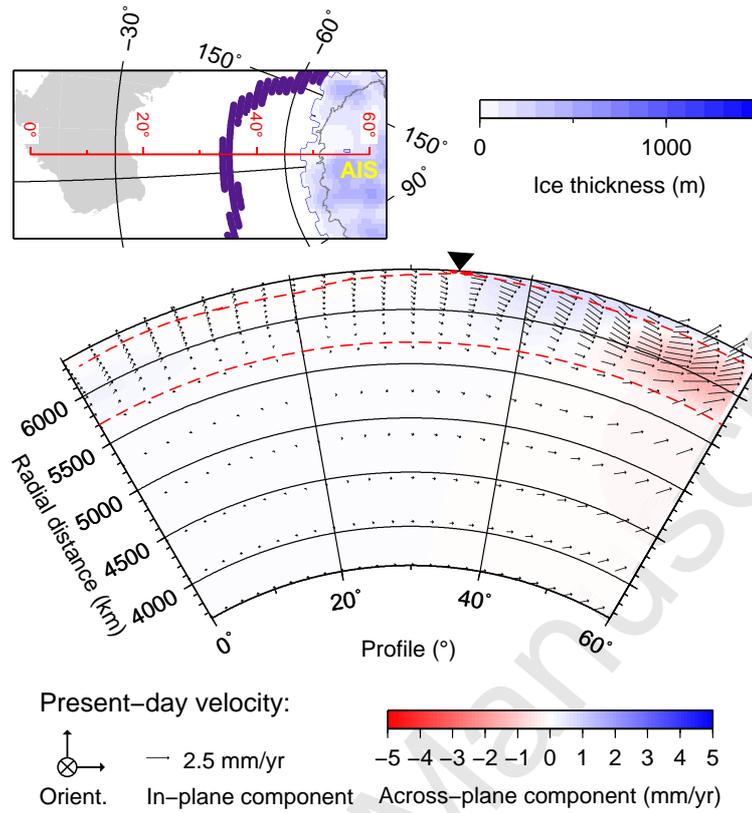


Fig. 7. Present-day GIA-induced velocities along a cross-section beginning in Australia, passing through the Southeast-Indian ridge and ending in the Antarctic ice sheet (AIS). For details see Figure 5.

earth model, while the change is much smoother in the prediction of the corresponding laterally homogeneous model. The top panel shows that the uplift rate is relatively little influenced by the presence of the ridge.

4. Influence of GIA on plate motion

The motion of tectonic plates is usually represented by a rigid motion around a rotation pole. In order to compare the GIA-induced motion with the geodetically inferred plate motion in Altamimi et al. (2007), we calculate the incremental rotation of individual tectonic plates from the GIA induced horizontal velocities at the sites provided in their Table 7 applying a least squares fit (Appendix, Eq. A.3). Table 1 shows the rotation poles and velocities given in Altamimi et al. (2007, Table 8) with those determined for the GIA-induced motion. For the chosen models, the largest rotation is exhibited in North America, as is shown in Figure A.1. The vectors west of the North American continental divide show the

considerable influence of the modeled plate boundaries (Figure 2). The latter facilitates an enhanced north-northwesterly and, consequently, a stronger rotation of the continent. This numerical experiment suggests that models of the geophysical forces that control North American plate motion might have to further consider GIA induced motions before advancing dynamical models that explain crustal motion at the 1–2 mm/yr level.

The model reference system is defined by fixing the center of mass and that no net rotation of the surface is allowed (Appendix, Eq. A.2). In order to compare the GIA induced poles with those of the observed plate motions, we subtract the respective GIA induced rotation vectors from the ITRF rotation vectors, $\Omega_{ITRF} - \Omega_{GIA}$ and consider the resulting changes in longitude, latitude and rotation velocity in the 4th to 7th column of Table 1. The rotational velocity of Antarctica and Europe are slightly reduced, whereas those of the Pacific and South American plate are unaffected by GIA. The other plates listed are enhanced by the effect of GIA. The shifts in the location of the rotation poles are at the

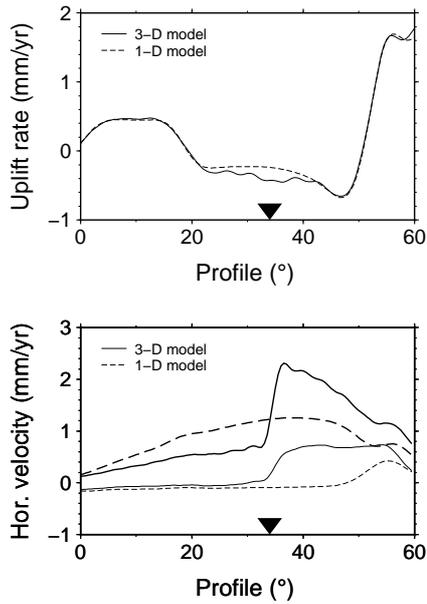


Fig. 8. Horizontal and vertical present-day GIA-induced surface velocities along the cross-section shown in Figure 7. Velocities for the cases where lateral variations in lithosphere thickness and the presence of the Southeast-Indian ridge are considered are plotted with solid lines (3-D) and where they are not considered with dashed lines (1-D). Thick and thin lines in the bottom panel denote the horizontal motion in- and perpendicular to the plane of the cross section, respectively. The inverted triangle denotes the position of the Southeast-Indian ridge.

level of about 1 degree. From the intercomparison of the perturbations considered here, we conclude that there is a ubiquitous influence of rheologically soft plate boundaries on plate rotations, intraplate horizontal velocities and on the generation of finite global toroidal deformation field. Each of these features may be detectable by modern space geodetic techniques.

5. Summary

This study shows that the GIA-induced horizontal velocities are globally of the order of 1 mm/yr, and are strongly influenced by lateral variations in lithosphere thickness and the presence of tectonic plate boundaries. The current level of accuracy in the detection of present-day horizontal motions approaches 1 mm/yr using space-geodetic techniques such as GPS. Therefore, GIA signals must be considered for modeling the mantle-wide dynamical causes of plate motion and of intraplate deformations. The present study essentially considers only one element of lateral variability, lithosphere thickness. Other

Table 1

Absolute rotation poles for different plates from ITRF2005 (1st line of respective plate), GIA-induced component for 1-D earth model (2nd line) and for 3-D earth model (3rd line). The 4th to 7th column presents the respective errors in the determination of the ITRF poles and below the corrections to the ITRF poles if they are reduced by the GIA induced components. The table is designed to show the influence of a plate structure, not to give a realistic prediction.

Plate	ITRF/GIA			error/corr.		
	Lon. (°E)	Lat. (°N)	Vel. (°/Myr)	Lon. (°E)	Lat. (°N)	Vel. (°/Myr)
Antarctica	-125.3	59.8	0.223	±1.7	±0.9	±0.007
	135.5	34.0	0.005	2.2	-0.6	-0.002
	150.3	28.8	0.008	3.6	-0.4	-0.004
Australia	37.4	32.4	0.628	±0.4	±0.3	±0.003
	-118.3	-3.9	0.009	0.4	-0.3	0.007
	-105.8	1.9	0.006	0.4	-0.2	0.004
Eurasia	-96.0	56.3	0.261	±1.0	±0.5	±0.003
	-52.4	-16.3	0.009	-2.4	1.4	-0.001
	-56.7	-13.0	0.006	-1.6	1.0	-0.001
N. America	-87.4	-4.3	0.192	±0.6	±0.9	±0.002
	153.7	3.5	0.004	1.1	-0.0	0.002
	136.5	-39.8	0.015	2.3	2.9	0.008
Pacific	112.9	-62.6	0.682	±0.7	±0.2	±0.004
	52.0	36.3	0.002	0.3	-0.1	0.001
	9.5	11.4	0.003	0.5	-0.0	0.001
S. America	-129.6	-16.8	0.121	±2.1	±1.6	±0.003
	-19.9	-18.4	0.008	-3.6	1.6	0.002
	-9.9	-27.0	0.006	-2.1	1.5	0.002

viscosity variations in the upper mantle have to be considered as shown by Wang and Wu (2006b) and Paulson et al. (2007). It should be noted that this study probes but one subset of the parameter space for predicting GIA-induced surface horizontal motion. Our results indicate the global importance of ongoing GIA in the interpretation of GPS time series for sites far away from the formerly glaciated areas, as these are non-negligible with respect to state-of-the-art kinematic and dynamic models of plate motion. The global consequences of GIA are amplified by the existence of soft plate boundaries. Further amplification could occur in model predictions that incorporate lateral variations of lithosphere thickness and variability in the mantle viscosity.

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Appendix A. Appendix

The spectral representation of the displacement field follows the notations in Martinec (2000), and splits the motion into a spheroidal part represented by U_{jm} and V_{jm} and a toroidal part W_{jm} :

$$\mathbf{u}(r, \Omega) = \sum_{j=0}^{j_{\max}} \sum_{m=0}^j [U_{jm}(r) \mathbf{e}_r Y_{jm}(\Omega) + V_{jm}(r) \nabla_{\Omega} Y_{jm}(\Omega) + W_{jm}(r) \mathbf{L}_{\Omega} Y_{jm}(\Omega)] \quad (\text{A.1})$$

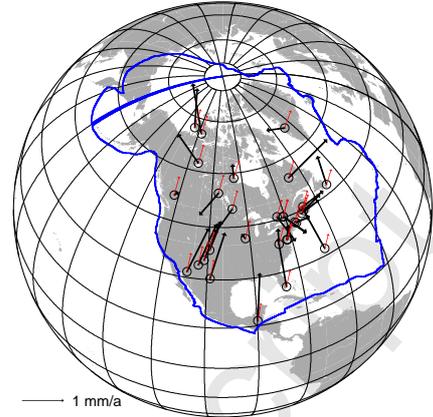
where r is the radial distance and $\Omega = (\theta, \phi)$ are the colatitude and longitude. The summations extend in Legendre degrees, j , from 0 to the maximum degree, j_{\max} , considered and in order m from 0 to j . $Y_{jm}(\Omega)$ are the normalized scalar spherical harmonics (e.g. Varshalovich et al., 1988). ∇_{Ω} denotes the angular part of the gradient operator and $\mathbf{L}_{\Omega} = \mathbf{e}_r \times \nabla_{\Omega}$ stands for the angular part of the angular momentum operator.

The conditions of center of mass invariance and no net rotation are considered by assuming that for each epoch

$$\int_{V_0} \mathbf{u} \rho dV = 0 \quad (\text{A.2})$$

$$\int_{\Omega_0} \mathbf{u} \times \mathbf{e}_r d\Omega = 0$$

(Lon=153.7 °E, Lat= 3.5 °N, $\Omega=4.2\text{e-}03$ °/Myr)



(Lon=136.5 °E, Lat=-39.8 °N, $\Omega=1.5\text{e-}02$ °/Myr)

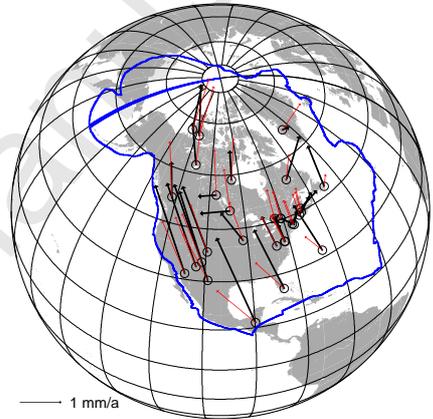


Fig. A.1. Horizontal present-day GIA-induced surface velocities for rigid plate sites of North America considered in the ITRF2005 (Altamimi et al., 2007) for the 1-D earth model (left) and 3-D earth model (right) of the analysis presented in the paper. Black arrows denote the induced surface velocities and red arrows the velocities due to a rigid rotation with parameters given at the top of each plot.

holds, where V_0 is the earth's volume, Ω_0 is the earth's surface, ρ is the material density, \mathbf{e}_r is the radial unit vector and $d\Omega = \sin \theta d\theta d\phi$.

In order to determine the rigid-plate rotation, we solve

$$\frac{1}{R} \begin{pmatrix} u_\theta(\theta_i, \phi_i) \\ u_\phi(\theta_i, \phi_i) \end{pmatrix} = \begin{pmatrix} -\sin \phi_i & \cos \phi_i & 0 \\ -\cos \theta_i \cos \phi_i & -\cos \theta_i \sin \phi_i & \sin \theta_i \end{pmatrix} \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} \quad (\text{A.3})$$

where R is the earth's radius. The displacement, u_θ, u_ϕ , at colatitude θ_i and longitude ϕ_i is given in polar coordinates originating from an incremental rotation vector $\boldsymbol{\omega} = \omega_x \mathbf{e}_x + \omega_y \mathbf{e}_y + \omega_z \mathbf{e}_z$ in Cartesian coordinates. The orientation of the Cartesian system with respect to the polar coordinates, (r, θ, ϕ) , is $\mathbf{e}_x = (1, \pi/2, 0)$, $\mathbf{e}_y = (1, \pi/2, \pi/2)$ and $\mathbf{e}_z = (1, 0, 0)$. The rotation vector is determined from the given displacement rates of the respective plate by applying a least-squares fit. The rotation pole then follows:

$$\begin{aligned} \Omega &= \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2}, \\ \Theta &= \arccos \frac{\omega_z}{\Omega}, \\ \Phi &= \arctan \frac{\omega_y}{\omega_x}. \end{aligned} \quad (\text{A.4})$$

Its geographical coordinates are $\Phi = \text{longitude}$ and $90^\circ - \Theta = \text{latitude}$. Figure A.1 shows as an example of Table 1 the predicted contribution to the plate motion of North America inferred from modelled velocities at the ITRF stations.