Tectonophysics 511 (2011) 99–108

Contents lists available at SciVerse ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Contribution of glacial-isostatic adjustment to the geocenter motion

Volker Klemann [a,*], Zdeněk Martinec [a,b,1]

[a] Helmholtz Center Potsdam, German Research Center for Geosciences, Sect. 1.5: Earth System Modelling, Telegrafenberg, D-14473 Potsdam, Germany
[b] Charles University, v Holešovičkách 2, 180 00 Prague 8, Czech Republic

ARTICLE INFO

Article history:
Received 6 July 2009
Received in revised form 13 August 2009
Accepted 31 August 2009
Available online 10 September 2009

Keywords:
Geocenter motion
Mantle viscosity
Glacial-isostatic adjustment
Static fluid-core approximation

ABSTRACT

The geocenter motion describes the surface net-displacement of the entire solid Earth with respect to the center-of-mass of the entire Earth including surface masses. Therefore, it resembles an integrative quantity of surface displacement and mass redistribution inside the Earth as well as at its surface. Seasonal variations of this quantity are understood to originate mainly from mass redistribution in the water cycle. In contrast, a secular trend of the geocenter motion is possible to result also from the dynamics of the Earth's interior. One mechanism inducing a secular geocenter motion is the glacial-isostatic adjustment, describing the deformation and mass redistribution in the Earth's interior due to glaciations during the Pleistocene. Focusing on this contribution, we compute the geocenter motion from the displacement and gravity-potential fields calculated for a spherical, self-gravitating, incompressible and viscoelastic Earth model loaded by the last Pleistocene glacial cycle. We discuss the fluid-core approximation usually adopted and assess the influence of a list of modelling parameters which are the upper- and lower-mantle viscosity, lithosphere thickness, and glaciation history. We find a rather robust geocenter motion with respect to parameter variations, which is directed towards Northeast Canada and shows velocities that vary between 0.1 and 1 mm/yr depending on the adopted Earth-model and glaciation-history parameterizations.

1. Introduction

Due to increasing accuracy in determining the Earth-orientation parameters, the geocenter (GC) motion becomes more important. We define it here according to Blewitt (2003) as the motion of the center-of-figure (CF), i.e. the ‘frame defined geometrically as though the Earth's surface were covered by a uniform, infinitely dense array of points’, against the center-of-mass (CM) of the entire Earth system including surface masses. Whereas the variations of surface masses in ocean, atmosphere, cryosphere and continental hydrology contribute the largest seasonal signal (e.g. Chen et al., 1999) long term variations can also be explained by mass redistributions in the Earth's interior.

The GC motion can be determined from a combination of observations like DORIS and LAGEOS (e.g. Bouillé et al., 2000), using GRACE tracking data (Kang et al., 2009), VLBI or GPS. A problem of this combination of ground-based and satellite data is the unequal distribution of observation points at the Earth's surface. As discussed in Blewitt (2003), a fiducial-free network displacement of GPS-stations should be possible to use for geodynamic constraints, if all non-gravitational forces contaminating the motion of the satellites would be known (Heflin et al., 1992). The seasonal signal is determined rather accurately (Blewitt et al., 2001; Dong et al., 2003; Lavallée et al., 2006) and its origin from the redistribution of surface masses is understood (Chen et al., 1999; Wu et al., 2006). The secular trend of the GC motion can also result from mass redistribution in the Earth's interior. As already suggested by Greff-Lefftz (2000), one candidate is the glacial-isostatic adjustment (GIA) which describes the adjustment of the Earth's interior after the last glacial cycle which terminated 8000 yr before present.

Recently, Argus (2007) assessed the contribution of GIA to this motion to be not larger than 0.1 mm/yr. He considered the main effect of GIA on the GC motion to be the mass change due to the uplift in Laurentide, determined this as a motion of the solid-Earth system (CE) against the CM according to Blewitt et al. (2001) and got a velocity of 0.034 mm/yr for the Earth-model/glaciation-history combination VM2/ICE-5G (Peltier, 2004). Determining the GIA-induced GC motion from the global surface-displacement field, Greff-Lefftz (2000) studied the dependence of GC motion on the viscosity contrast between upper and lower mantle and predicted values of up to 0.4 mm/yr, where she considered the glaciation history ICE3G (Tushingham and Peltier, 1991). Furthermore, applying a formal inversion, Wu et al. (Submitted for publication) assessed a value of 0.7 mm/yr for the contribution of GIA.

Based on the numerical technique of Martinec (2000), we revisit the calculation of the GC motion for a viscoelastic non-rotating planet and present the uniqueness conditions for determining the GIA-induced deformation.

Furthermore, we discuss the influence of the fluid-core approximation, often applied in modelling of GIA. This approximation considers the

* Corresponding author.
E-mail address: volkerk@gfz-potsdam.de (V. Klemann).
[1] Present address: Now at Dublin Institute for Advanced Studies, 5 Merrion Square, Dublin 2, Ireland.

0040-1951/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2009.08.031

influence of the fluid core as a boundary condition at the core–mantle boundary assuming the core as a self-gravitating fluid persisting to remain in a hydrostatic state (Crossley and Gubbins, 1975). The presented model is applied to Earth-model/glaciation-history combinations, the influence of lower- and upper-mantle viscosity on GC motion is discussed and the influence of the chosen glaciation history is shown.

The study is based on the solution strategy of solving the field equations with a spectral finite element method (SFEM) suggested by Martinec (2000). There, the radial dependence of the fields is solved by finite elements whereas the lateral dependence is set up in spherical harmonics. The time dependence of the viscous flow is solved directly in the time domain omitting the usually considered normal mode theory in the Laplace domain (Wu and Peltier, 1982). Due to the chosen setup of the system of equations and in addition to boundary conditions which resemble the loading process, six uniqueness conditions have to be specified. In order to prohibit a net translation, the usual choice is to consider the CM or, alternatively, to consider the CF to be invariant with respect to the loading process. A second set of uniqueness conditions is related to the rotation of the body. Here we consider the ITRF convention of no surface net rotation (e.g. Kreemer et al., 2006).

In this study, we aim at emphasizing a significant influence of lower-mantle viscosity on a GC motion. The Earth-model/glaciation-history combination VM2/ICE-5G of Peltier (2004) results in a GC motion of about 0.1 mm/yr (Argus, 2007), which can partly be explained by a small lower-mantle viscosity considered in VM2. Predictions of the $\dot{J}_2$-term by GIA and comparison to true polar wander suggest a significant viscosity contrast between upper and lower mantle of at least one order of magnitude (Vermeersen et al., 1998). Furthermore, Greff-Lefftz (2000) already showed that considering the glaciation history ICE3G (Tushingham and Peltier, 1991) and a viscosity contrast of 10 between lower and upper mantle amplifies the GC motion to 0.5 mm/yr.

2. Theoretical background

Since the viscoelastic response of the Earth induced by glacial loading has a global feature, it is convenient to treat it in spherical coordinates and parameterize field variables in terms of surface spherical harmonics. Such a parameterization is used, for instance, in Peltier (1974), Wu and Peltier (1982) and Martinec (2000). Here, we introduce the representation of the Eulerian gravitational-potential increment, ϕ^E, and the displacement vector, $\boldsymbol{u}$, and refer to Martinec (2000) for parameterization of other field variables. For a fixed time, ϕ^E and $\boldsymbol{u}$ depending on co-latitude and longitude, $\Omega=(\theta,\varphi)$, are expanded in a series of scalar and vector spherical harmonics, respectively:

$$\begin{aligned}\phi^{E}(r,\Omega) &= \sum_{j=0}^{\infty}\sum_{m=-j}^{m=j} F_{jm}(r)Y_{jm}(\Omega)\,,\\ \boldsymbol{u}(r,\Omega) &= \sum_{j=0}^{\infty}\sum_{m=-j}^{m=j}\left[U_{jm}(r)\boldsymbol{S}_{jm}^{(-1)}(\Omega)+V_{jm}(r)\boldsymbol{S}_{jm}^{(-1)}(\Omega)+W_{jm}(r)\boldsymbol{S}_{jm}^{(0)}(\Omega)\right],\end{aligned} \tag{1}$$

where $0\le r\le a$ with a the radius of the Earth and r the radial distance. The quantities $[F, U, V, W]_{jm}$ represent the spectral components, and Y_{jm} and $\boldsymbol{S}_{jm}^{(\lambda)}$ are the respective scalar and vector spherical harmonics, see Appendix A. The summations spread over the angular degree j and azimuthal order m. The potential is defined according to

$$\nabla^2\phi^E + 4\,\pi\,G\,div\,(\rho_0\boldsymbol{u}) = 0\,. \tag{2}$$

The representation of ϕ^E and $\boldsymbol{u}$ in fully normalised spherical harmonics enables easy derivation of the equations for GC motion by applying the formalisms outlined in the theory of angular momentum (Varshalovich et al., 1988). We solve the field equations directly in the time domain and do not apply any Love-number approach.

The degree-1 terms of the surface displacement, U_{1m} and V_{1m}, describe net translations relative to the considered reference system. Among them, the center-of-figure (CF) motion is of most interest which describes the integral motion of the surface, as if it would be equally covered by an infinite dense array of points (Blewitt, 2003). In contrast, the degree-1 term of the surface displacement, W_{1m}, describes a surface net rotation and is set to zero as one uniqueness condition. The center-of-mass (CM) motion is defined by the first moment of the mass redistribution of the whole Earth (Blewitt, 2003). The difference between CF and CM motions, the geocenter (GC) motion, is of special interest due to its invariance with respect to the chosen reference frame.

2.1. Center-of-figure motion

In the dynamic modelling of the motions due to a surface loading, we define a reference-state configuration of the Earth and define a reference system describing the position of mass points in this configuration. Here, the reference state describes the equilibrium state of a hydrostatically prestressed Earth where the reference system coincides with the reference configuration. Therefore, CF and CM coincide with the origin of the reference system. The variation of CF with respect to the origin of the reference system is defined by the net displacement of the surface. Considering Eq. (1), this results in

$$\begin{aligned}\boldsymbol{u}_{cf} :&= \frac{1}{A}\int_{\partial V}\boldsymbol{u}dS\\ &= \frac{1}{4\pi}\int_{\Omega_0}\sum_{jm}\left[U_{jm}\boldsymbol{S}_{jm}^{(-1)}+V_{jm}\boldsymbol{S}_{jm}^{(1)}+W_{jm}\boldsymbol{S}_{jm}^{(0)}\right]d\Omega\,,\end{aligned} \tag{3}$$

where ∂V is the surface of the Earth and $\Omega_0=4\pi$ is the full solid angle.

Solving the integral, the Cartesian components of this motion are

$$\begin{aligned}u_{cf}^{x} &= -\frac{1}{2}\sqrt{\frac{2}{3\pi}}\mathrm{Re}\{U_{11}+2V_{11}\}\,,\\ u_{cf}^{y} &= \frac{1}{2}\sqrt{\frac{2}{3\pi}}\mathrm{Im}\{U_{11}+2V_{11}\}\,,\\ u_{cf}^{z} &= \frac{1}{2}\sqrt{\frac{1}{3\pi}}(U_{10}+2V_{10})\,,\end{aligned} \tag{4}$$

where $\mathbf{e}_x$, $\mathbf{e}_y$ and $\mathbf{e}_z$ are the Cartesian base vectors (see Appendix A). Here, one has to bear in mind that only these linear combinations describe a surface displacement, whereas the remaining parts, $\boldsymbol{u}(U_{1m}, V_{1m})-\boldsymbol{u}_{cf}$, describe a deformation.

2.2. Center-of-mass motion

The CM motion represents the motion of the first moment. Due to MacCullagh theorem (Munk and Macdonald, 1960), we define it here as the translation necessary to achieve the configuration where the degree-1 components of the gravitational potential, ϕ^E in Eq. (1) vanish. Representing the displacement vector of the center-of-mass, u_{cm}, in Cartesian coordinates, we obtain as outlined in Appendix B.1

$$\begin{aligned}u_{cm}^{x} &= \frac{3}{2g_0}\sqrt{\frac{2}{3\pi}}\mathrm{Re}\{F_{11}\} = \frac{1}{g_0}\sqrt{\frac{3}{2\pi}}\mathrm{Re}\{F_{11}\}\\ u_{cm}^{y} &= -\frac{3}{2g_0}\sqrt{\frac{2}{3\pi}}\mathrm{Im}\{F_{11}\} = -\frac{1}{g_0}\sqrt{\frac{3}{2\pi}}\mathrm{Im}\{F_{11}\}\\ u_{cm}^{z} &= -\frac{3}{2g_0}\sqrt{\frac{1}{3\pi}}F_{10} = -\frac{1}{2g_0}\sqrt{\frac{3}{\pi}}F_{10}\end{aligned} \tag{5}$$

where g_0 is the surface gravity and F_{1m} are the degree-1 components of the potential increment ϕ^E due to internal- and surface-mass redistribution.