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Applying local Green's functions to study the influence of the crustal structure on hydrological loading displacements

R. Dill[a,*], V. Klemann[a], Z. Martinec[b,c], M. Tesauro[a,d]

[a] Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, Section 1.3: Earth System Modelling, Germany
[b] Charles University in Prague, Czech Republic
[c] DIAS – Dublin Institute of Advanced Studies, Ireland
[d] Utrecht University, The Netherlands

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ABSTRACT

The influence of the elastic Earth properties on seasonal or shorter periodic surface deformations due to atmospheric surface pressure and terrestrial water storage variations is usually modeled by applying a local half-space model or an one dimensional spherical Earth model like PREM from which a unique set of elastic load Love numbers, or alternatively, elastic Green's functions are derived. The first model is valid only if load and observer almost coincide, the second model considers only the response of an average Earth structure. However, for surface loads with horizontal scales less than 2500 km^2, as for instance, for strong localized hydrological signals associated with heavy precipitation events and river floods, the Earth elastic response becomes very sensitive to inhomogeneities in the Earth crustal structure.

We derive a set of local Green's functions defined globally on a $1^\circ \times 1^\circ$ grid for the 3-layer crustal structure TEA12. Local Green's functions show standard deviations of ±12% in the vertical and ±21% in the horizontal directions for distances in the range from 0.1° to 0.5°. By means of Green's function scatter plots, we analyze the dependence of the load response to various crustal rocks and layer thicknesses. The application of local Green's functions instead of a mean global Green's function introduces a variability of 0.5–1.0 mm into the hydrological loading displacements, both in vertical and in horizontal directions. Maximum changes due to the local crustal structures are from −25% to +26% in the vertical and −91% to +55% in the horizontal displacements. In addition, the horizontal displacement can change its direction significantly. The lateral deviations in surface deformation due to local crustal elastic properties are found to be much larger than the differences between various commonly used one-dimensional Earth models.

1. Introduction

Temporal mass changes in the Earth system, that reflect changes in atmospheric surface pressure, ocean bottom pressure, and terrestrial water storage, lead to both gravity field variations and deformations at the Earth's surface, which are associated with the mass redistribution at the surface and the respective loading response of the Earth's interior. In contrast to tidal-induced surface mass variations, which are dominated by ocean processes, non-tidal mass variations with subdaily to seasonal periods are primarily acting over land as they are caused by atmospheric circulation and hydrological mass transport (e.g. Tregoning et al., 2009; Rajner and Liwosz, 2011; Fritsche et al., 2012). The global-scale gravity field variations are observed by the Gravity Recovery and Climate Experiment (GRACE) satellite mission, whereas space geodetic techniques such as the Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging allow the measurements of site position displacement. Atmospheric surface pressure and terrestrial water storage generate elastic deformations that are large enough to be detected with space geodetic techniques on global (Blewitt et al., 2001), regional (Fu et al., 2012) and local scales (Bevis, 2005). Elastic surface deformations have to be taken into account for the realization of terrestrial reference frames as they can affect epoch-wise parameters causing a significant loss in solution accuracy (Dach and Dietrich, 2000), or for the correction of regional geodetic surveys.

Site-specific load deformations can be calculated from observed or simulated atmospheric and hydrological mass variations. As mass variations induce deformation fields of principally global

* Corresponding author. Tel.: +49 331 288 1750.
E-mail address: dill@gfz-potsdam.de (R. Dill).

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extent, a large area around each station has to be taken into account. Global mass re-distributions are accessible from global numerical weather models, global hydrospheric models, or can be derived from gravity field variations as given by the satellite mission GRACE (Van Dam et al., 2007, 2011). The displacement fields due to short-periodic surface loading processes are calculated with numerical models using the load Love numbers, or the Green's function approach introduced by Farrell (1972). Load Love numbers represent the spectral elastic response of a spherically symmetric, layered Earth structure to a unit mass that loads the Earth surface at the north pole. Widely used Earth's models are G–B (Gutenberg–Bullen A: see e.g. Alterman et al., 1961), PREM (Dziewonski and Anderson, 1981), or ak135 (Kennett, 1995). To derive Green's functions from the corresponding load Love numbers, the Earth's response to a point-load is calculated under the assumption that the elastic properties do not differ laterally. This implies that the considered loads extend over thousands of km. The sensitivity of the elastic response to inhomogeneities in the Earth's crust increases significantly for surface loads with horizontal scales less than 2500 km^2, such as hydrological mass load signals associated with heavy precipitation events, river floods, and the periodic filling of dams. Therefore, displacement signals observed by GPS (Jiang et al., 2013; Williams and Penna, 2011; Rajner and Liwosz, 2011) and VLBI (Petrov and Boy, 2004) reveal site-specific signatures originating from distinctive characteristics of the shallow elastic structure of the Earth's crust beneath the station (e.g. Fu et al., 2012; Bevis, 2005), an aspect which is not considered in traditional loading calculations based on Green's functions. According to their designated application, the traditional Green's functions are often only roughly categorized, e.g. into only soft, medium, or hard crustal rheologies (Wang et al., 2012). Although such models are rather common in geodetic applications, they suffer from their global 1-dimensional symmetry.

Wang (2000) constructed site-dependent Green's functions based on a local layered crustal structure consisting of sediments, crystalline basement, middle crust, and lower crust in order to provide load correction models for GPS observations in the front Three Gorges Reservoir area that are accurate enough to discriminate between earthquake-related crustal motion and height changes that occur due to reservoir impoundment (Wang et al., 2002). Gegout (2013) followed the same approach to present site-dependent Love numbers for specific geodetic observation sites taking into account the specific radial Earth structure below each site. Implicitly, this approach assumes spherically symmetric Earth models, each with the respective site-specific crustal structure. Recently, Wang et al. (2013) and Chanard et al. (2014) followed the reverse strategy and inferred an averaged elastic Earth structure for the Himalayan region from the consideration of observed loading processes.

In this study, we will resume the approach of site-dependent Green's functions, but not only for a small number of geodetic site locations but for a global assessment of uncertainties in calculating atmospheric and hydrological loading displacements.

Based on the laterally variable continental crust model provided by Tesauro et al. (2012) (here named TEA12), we determined local Green's functions on a global regular grid, see Section 2. The deviation of the local response from that of the 1-dimensional Earth models is discussed in Section 3 together with their applicability to the global representation of hydrological water loads including local structures like rivers and lakes as well as regional loads due to soil moisture or snow accumulation. In Section 4 a one-year simulation of global hydrological and non-tidal atmospheric loading is presented in order to figure out the maximum influences of crustal inhomogeneities on geodetic displacement observations.

2. Determination of local Green's functions

When discussing load responses induced by short-periodic mass variations like terrestrial water storage or atmospheric surface pressure variations with subdaily to annual periods, the purely elastic response of the Earth is a good first order approximation. Anelasticity or viscoelasticity, which have to be considered for processes like postseismic deformation or postglacial rebound, take place on longer time scales and will be neglected here. Assuming only purely elastic deformation, the response is instantaneous and superposition principle can be applied. Representing the surface-mass load in spherical harmonic coefficients of Legendre degrees, n, and order, m, its changes can be related to the spherical harmonic coefficients of the vertical and horizontal deformations, and geoid changes through degree-dependent load Love numbers. Farrell (1972) outlines the calculation of properly weighted sums of the load Love numbers for a given Earth model to form Green's functions. For a unit point mass, 1 kg, the vertical (radial) displacement, G_r, and horizontal displacement, G_h, at a distance Θ from the point mass can be derived from the load Love numbers h_n and l_n by

$$\begin{aligned} G_r(\Theta) &= \frac{a}{m_e}\sum_{n=0}^{\infty} h_n P_n(\cos\Theta) \\ G_h(\Theta) &= \frac{a}{m_e}\sum_{n=1}^{\infty} l_n \frac{\partial P_n(\cos\Theta)}{\partial\Theta} \end{aligned} \quad (1)$$

with Earth's radius a and Earth's mass m_e. Similarly, Green's functions for other quantities like the gravity change, strain, or tilt caused by a surface-mass load can be derived (not discussed in this study).

Assigning Eq. (1) to any extended mass distribution, the displacement field, $\boldsymbol{u}$, is given by a convolution integral over the loaded region, Ω, as

$$\begin{aligned} u_r(\boldsymbol{r}') &= \int_\Omega G_r(\Theta) L(\boldsymbol{r})\, d\Omega, \\ \boldsymbol{u}_h(\boldsymbol{r}') &= \int_\Omega \hat{q}(\boldsymbol{r},\boldsymbol{r}') G_h(\Theta) L(\boldsymbol{r})\, d\Omega. \end{aligned} \quad (2)$$

Here, $L(\boldsymbol{r})$ denotes the surface mass load at the location $\boldsymbol{r}(a, \lambda, \varphi)$ with longitude λ and latitude φ, $\boldsymbol{r} \in \Omega$. $\boldsymbol{r}'$ denotes an observation point (station), and $\hat{q}(\boldsymbol{r}, \boldsymbol{r}')$ is the unit vector originating from the station, tangential to the Earth's surface, which lies in the plane determined by the radius vectors to the station and to the mass load. The distance Θ between mass load and station is given by the angular distance $\Theta = \arccos(\boldsymbol{r} \cdot \boldsymbol{r}'/a^2)$.

As the convolution takes place in the spatial domain, the Green's function approach is especially useful if the spherical harmonic representation of the surface-mass load is dominated by high-degree Stokes Coefficients ($n > 1000$), as for instance, in the case of the highly heterogeneous distribution of terrestrial water storage.

In the calculation of load Love numbers, a customary idealization of the Earth is a model composed of spherically symmetric layers. The various acceptable global Earth models differ only slightly in their low-degree response. For higher degrees, the geological structure of the crust becomes relatively important. As consequence, a single spherically symmetric Earth model cannot represent the Earth's extremely heterogeneous outermost 50 km accurately enough for small-scale surface loads. For local geodetic deformation studies, one needs to re-compute the Green's functions from a set of load Love numbers valid for the specific region that considers the regional deviation of the Earth's elastic response with respect to the global mean. Introducing such locally defined