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Empirical model of the gravitational field generated by the oceanic lithosphere

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Abstract

We present an empirical model of the gravitational field generated by the oceanic lithosphere computed over the world's oceans with a spectral resolution complete to a spherical harmonic degree of 180. This gravity model is compiled based on applying methods for a spherical harmonic analysis and synthesis of the global gravity and crustal structure models. The *in situ* seawater densities and the density samples from ocean-floor drilling sites are utilized in the gravimetric forward modeling of bathymetry and marine sediments. The gravitational signal attributed to the oceanic lithosphere density structure is described empirically in terms of the ocean-floor age and depth. The former is explained by the increasing density with age due to conductive cooling of the oceanic lithosphere. The latter describes the gravitational signature of thermal lithospheric contraction, which is isostatically compensated by ocean deepening. The long-wavelength gravity spectrum reflects mainly the compositional and thermal structures within the sub-lithospheric mantle. We demonstrate that this empirical gravity model reproduces realistically most of the long-to-medium wavelength features of the actual gravity field, except for some systematic discrepancies, especially along continental slopes and large sedimentary accumulations, which cannot be described accurately by applied empirical models.

Keywords: Density; Gravity; Ocean-floor spreading; Oceanic lithosphere

1. Introduction

Several different global models describing the Earth's structure by means of seismic velocities and/or mass density were developed based on the analysis of available seismic data. Dziewonski and Anderson (1981) presented the Preliminary Reference Earth Model (PREM), which provides information on the seismic velocities and density structure within the whole Earth's interior (including the core and mantle) by means of spherically homogenous stratigraphic layers. More recently, Simmons et al. (2010) developed the GyPSuM tomographic model of the mantle (P and S) seismic velocities and density through a simultaneous inversion of seismic body wave travel times and geodynamic observables including the free-air gravity anomalies, tectonic plate divergence, dynamic surface topography and the excess ellipticity of the core-mantle boundary. They also incorporated mineral physics constraints in order to link seismic velocities and wave speeds with an underlying hypothesis that temperature is a principal cause of heterogeneities in the non-cratonic mantle. In addition to these Earth's synthetic models, several other global and regional seismic velocity models were developed. For more details we refer readers also to studies by Kennett and Engdahl (1991), Kennett et al. (1995), Montagner and Kennett (1995), van der Lee and Nolet (1997), Grand et al. (1997), Megnin and Romanowicz (2000), Grand (2002), Gung and Romanowicz (2004), van der Lee and Frederiksen

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(2005), Panning and Romanowicz (2006), Houser et al. (2008), Kustowski et al. (2008a,b), Bedle and van der Lee (2009), Panning et al. (2010), Obrebski et al. (2010, 2011), Porritt et al. (2011), James et al. (2011), Lekic and Romanowicz (2011) and Simmons et al. (2012), and others. Summary of these models can also be found in Trabant et al. (2012). The seismic data were also used to compile the global crustal models CRUST5.1 (Mooney et al., 1998) and CRUST2.0 (Bassin et al., 2000). The most recent version, CRUST1.0 (Laske et al., 2012), provides the crustal structure on a 1×1 arc-deg global grid. The CRUST1.0 consists of the ice, water, (upper, middle and lower) sediments and (upper, middle and lower) consolidated (crystalline) crustal layers and also incorporates the lateral upper mantle density structure. Chen and Tenzer (2014) compiled the global spectral crustal model ESCM180 based on refining the CRUST1.0 by using additional crustal structure and density models.

Methods for a gravimetric forward modeling can be applied to compute the Earth's gravity field from the 3-D Earth's density model. Alternatively, the synthetic gravity models can be prepared using information on the solid topography and adopting some isostatic hypothesis. For more information on applied methods and existing synthetic regional and global gravity models we refer readers to studies, for instance, by Sünkel (1981), Sünkel (1985), Rummel et al. (1988), Pail (2000), Haagmans (2000), Claessens (2002), Featherstone (2002), Holmes (2002), Kuhn and Featherstone (2003, 2005), Tsoulis (2001), Ågren (2004) and Bagherbandi and Sjöberg (2012a).

In this study we developed the empirical gravitational model of the oceanic lithosphere and applied it in combination with the gravitational contributions of the crustal density structures to compile the gravity field over the world's oceans. This empirical model describes the gravitational signal of the oceanic lithosphere by means of conductive cooling and thermal contraction which is isostatically compensated by ocean deepening (e.g., Williams, 1975; Parsons and Sclater, 1977). The methodology is summarized in Section 2. The numerical procedures are reviewed in Section 3. The results are presented and discussed in Sections 4 and 5. The conclusions are given in Section 6.

2. Method

To compile the gravity field over the world's oceans, we formally subdivided the Earth's inner structure into individual volumetric mass layers consisting of the continental crustal structures (topography, polar ice sheets and sedimentary basins), the oceanic lithosphere (including bathymetry and marine sediments) and the sub-lithospheric mantle heterogeneities. We also took into consideration the gravitational signature of the Moho density interface. The gravity disturbance δg is then evaluated according to the following scheme

$$\delta g = g^T + g^B + g^I + g^S + g^{Moho} + \delta g^m, \tag{1}$$

where g^T, g^B, g^I and g^S are, respectively, the gravitational contributions of topography, bathymetry, polar ice sheets and sediments, and g^{Moho} is the Moho gravitational signature. The last term in Eq. (1) defines the mantle gravity disturbance δg^m, which comprises the gravitational contribution of the oceanic lithosphere g^{ol} and the sub-lithospheric mantle gravity disturbance δg^{slm}. We then write

$$\delta g^m = g^{ol} + \delta g^{slm}. \tag{2}$$

We applied methods for a spherical harmonic analysis and synthesis of the global gravity and crustal structure models to evaluate the gravitational components g^T, g^B, g^I, g^S and g^{Moho}. Since the sub-lithospheric mantle heterogeneities (including the core–mantle boundary zone; cf. Peltier, 2007) mostly contribute to the long-wavelength gravity spectrum (e.g., Sjöberg, 2009), we computed the respective gravity disturbances δg^{slm} from low-degree coefficients of a global gravity model. The gravitational component of the oceanic lithosphere was described by an empirical model. The expressions applied for a gravimetric forward modeling are reviewed next.

2.1. Gravimetric forward modeling

The gravitational contributions of known mass density structures were computed according to the following expression (cf. Tenzer et al., 2012a, 2012b)

$$g(r, \phi, \lambda) = \frac{GM}{R^2} \sum_{n=0}^{\bar{n}} \sum_{m=-n}^{n} \left(\frac{R}{r}\right)^{n+2} (n+1) V_{n,m} Y_{n,m}(\phi, \lambda), \tag{3}$$

where $GM = 3.986005 \times 10^{14}$ m^3/s^2 is the geocentric gravitational constant, $R = 6371 \times 10^3$ m is the Earth's mean radius, $Y_{n,m}$ are the spherical harmonics of degree n and order m, $\bar{n}$ is the maximum degree of spherical harmonics, and r, ϕ, λ are spherical coordinates (radius, latitude and longitude). The potential coefficients $V_{n,m}$ in Eq. (3) read

$$V_{n,m} = \frac{3}{\bar{\rho}^{Earth}(2n+1)} \sum_{i=0}^{I} \left(F1^{(i)}_{n,m} - Fu^{(i)}_{n,m} \right), \tag{4}$$

where $\bar{\rho}^{Earth} = 5500$ kg/m^3 is the Earth's mean density, and the coefficients $\{Fl^{(i)}_{n,m}, Fu^{(i)}_{n,m} : \; i = 0, 1, \ldots, I\}$ are given by

$$\begin{aligned} Fl^{(i)}_{n,m} &= \sum_{k=0}^{n+2} \binom{n+2}{k} \frac{(-1)^k}{k+1+i} \frac{L^{(k+1+i)}_{n,m}}{R^{k+1}}, \\ Fu^{(i)}_{n,m} &= \sum_{k=0}^{n+2} \binom{n+2}{k} \frac{(-1)^k}{k+1+i} \frac{U^{(k+1+i)}_{n,m}}{R^{k+1}}. \end{aligned} \tag{5}$$

The terms $\sum_{m=-n}^{n} L_{n,m} Y_{n,m}$ and $\sum_{m=-n}^{n} U_{n,m} Y_{n,m}$ define the spherical lower-bound and upper-bound laterally distributed radial density variation functions L_n and U_n respectively. These spherical functions and their higher-order terms $\{L^{(k+1+i)}_n, U^{(k+1+i)}_n : \; k = 0, 1, \ldots; \; i = 1, 2, \ldots, I\}$ are defined by means of the integral convolutions: