Journal of Asian Earth Sciences 59 (2012) 240–248

Contents lists available at SciVerse ScienceDirect

Journal of Asian Earth Sciences

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

Combination of seismic and an isostatic crustal thickness models using Butterworth filter in a spectral approach

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ARTICLE INFO

Article history:
Received 10 February 2012
Received in revised form 25 July 2012
Accepted 16 August 2012
Available online 28 August 2012

Keywords:
Crustal thickness
Isostasy
Moho depth
CRUST2.0

ABSTRACT

In this study, using Butterworth filter a combined crustal thickness model based on seismic and isostatic-gravimetric models is presented in a spectral domain. Vening Meinesz–Moritz isostatic model and a seismic model which obtained from sparse seismic data are two models used in this study. The filter used helps to join two models without any jump in the overlap degree in the spectral domain. The main motivations of this study are (a) presenting a higher resolution for the crustal thickness and (b) removing non-isostatic effects from the isostatic model. The result obtained from the combined model is a synthetic Earth crustal model up to degree 180 (equivalent resolution $1^\circ \times 1^\circ$). In spite of the differences in the some parts of the Earth between the seismic and isostatic-gravimetric models, the test computations show a satisfactory agreement between the results provided. Numerical results show that this method of combination agrees with the seismic crustal thickness (about 2.0 km rms difference).

1. Introduction

The *Mohorovičić discontinuity*, usually called the *Moho*, is the boundary between the Earth's crust and mantle. In accurate definition, the Moho is simply a physical/chemical boundary between the crust and mantle where both the crust and mantle are defined by material properties, which can cause large changes in geophysical properties, such as seismic wave velocity, density, pressure, temperature, etc. (Mooney et al., 1998; Kaban et al., 2003; Martinec, 1994). The crustal thickness is great interest among geoscientists. It can be determined by seismic and gravimetric methods. The global seismic crustal thickness models suffer from lack of global coverage of data, while the gravimetric methods use inexpensive and mostly already available global and regional gravity data using an isostatic model. The main reasons for studying the isostatic models are on one hand the gaps and uncertainties of the seismic models, and, on the other hand, the generous availability of gravity data from global models for the gravimetric-isostatic model. Several isostatic hypotheses and seismic model exist for estimating the crustal thickness and density of the Earth's crust, and it is not clarified which one is the most suitable to use in geophysical and geodynamical applications. The isostatic models are well-known from the literatures (see e.g. Heiskanen and Moritz, 1967, p. 133; Moritz, 1990, Chapter 8; Sjöberg, 2009; Bagherbandi, 2011). Among them the model presented by Sjöberg (2009), Vening Meinesz–Moritz (VMM) model, is the newest one.

Seismic observations have been collected in many tectonically active regions such as the mid-ocean ridges, oceanic plateaus and continental rifts. Soller et al. (1982) presented an early global seismic crustal model for the crustal thickness, and Nataf and Ricard (1996) presented a model for the crust and upper mantle on a $2^\circ \times 2^\circ$ grid, based on both seismic and non-seismic data (such as chemical composition and heat flow).

Čadak and Martinec (1991) presented a model for the crustal thickness in terms of the spherical harmonics to degree and order 30 based on different sources of seismic data. It is one of the first global crustal models that was presented by them. In fact they tried to represent the information about the topography of the crust-mantle boundary was compiled from various sources. Source material used for constructing the spherical harmonic expansion of the crustal thickness in Čadak and Martinec (1991) model were the seismic data produced by (1) Meissner et al. (1987), (2) Belyaevsky (1981), (3) Belyaevsky and Volkovsky (1980), (4) Allenby and Sehnetzler (1983), (5) Goslin et al. (1972), (6) using a uniform crustal thickness 7 km in Artic ocean, Southern ocean, Indian ocean, South Atlantic ocean, (7) using crustal thickness 7 km and topographic correction in Tasman sea, Coral sea and New Zealand, (8) using uniform crustal thickness 35 km in North of Canada (see more details in Čadak and Martinec, 1991, Fig. 1). In this model for oceanic regions with a considerable local topography (for islands), an appropriate topographic correction was considered (e.g. in New Zealand).

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1367-9120/$ - see front matter
http://dx.doi.org/10.1016/j.jseaes.2012.08.008

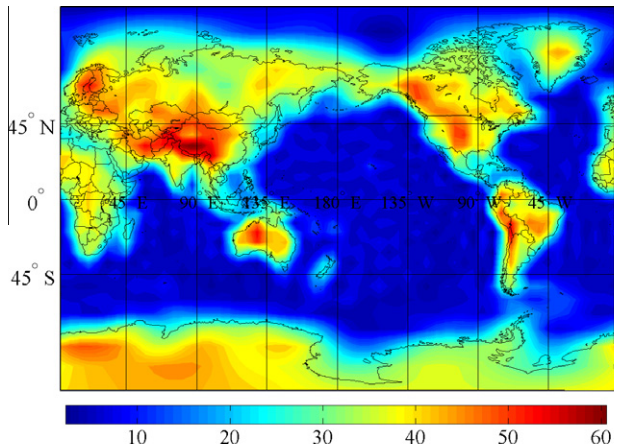

Fig. 1. CM91 crustal thickness with a grid size of $6^\circ \times 6^\circ$. Unit: km.

Another global seismic crustal models are CRUST5.1 (Mooney et al., 1998) and CRUST2.0 (Bassin et al., 2000), with resolution of $5^\circ \times 5^\circ$ and $2^\circ \times 2^\circ$, respectively. The model of Čadak and Martinec (1991) is similar to CRUST5.1 and they used same database. The accuracies of CRUST5.1 and CRUST2.0, the same as model of Čadak and Martinec (1991), are not specified; they vary in different places. For example, the accuracies of these models seem to be better in the United States and Europe because of dense seismic measurements (Mooney et al., 1998, Fig. 1), but much worse in Africa, Greenland, some parts of Asia and Antarctica. For these regions the crustal thickness was estimated by some interpolation method. These problems that were experienced in the seismic models encourage us to study the gravimetric approach as well as the combination of seismic and gravimetric crustal thickness.

The aim of this study is combination of a low resolution seismic crustal thickness model with an isostatic one (VMM). The result is called a Synthetic Earth Crustal Thickness (SECT). Sjöberg and Bagherbandi (2011) used CRUST2.0 and the VMM gravimetric-isostatic model to estimate a combine solution of the crustal thickness and the crust-mantle density contrast using least-square adjustment. In fact, they presented a synthetic crustal thickness which obtained from both seismic and gravimetric-isostatic models. Later Eshagh et al. (2011) presented a combined global model for the crustal thickness computed based on a stochastic combination of seismic and gravimetric crustal thicknesses. The major benefit of the gravimetric-isostatic models is its ability to use precise and uniform global coverage of the gravity data. They constructed condition adjustment models and took advantage of the variance component estimation process to get a statistically optimal spectral combination of the crustal thicknesses. The main application of the SECT is filling the gaps in areas which the data are poor. Presence of the data gaps in the global seismic models is the reason to study a higher resolution of the Earth crustal model based on the combination various data in estimation of the SECT. In this study we use the seismic crustal thickness published by Čadak and Martinec (1991), we call this model CM91 hereafter. Here the main reason for studying a SECT is similarity and high correlation between the degree variances of the CM91 and the VMM model. Other reason of the combination of seismic and isostatic data is reducing disturbing signals from the gravity data in the isostatic one. We know that the isostatic models suffer from some problems due to geophysical phenomena such as mantle convection, post-glacial rebound and plate tectonic. These are the disturbing signals or in a better term they are non-isostatic effects in estimation of the crustal thickness. A main objective in solid Earth and estimation of the crustal thickness from isostatic method is to decompose the gravity data into its individual contributions. It is difficult to decompose that up to which degree of gravity field (in the spectral domain) is related to crust only. Therefore using the practical method presented in this study, we are going to remove the above mentioned problems.

2. Crustal thickness models

In this section, we present the crustal thickness models applied in this study, which are the CM91 and the VMM isostatic-gravimetric model.

2.1. Čadek and Martinec' crustal thickness model

As mentioned before, the model presented by Čadak and Martinec (1991) are based on different source material. They tried to compile a crustal thickness model based on spherical harmonic expansion. For this purpose, if we assume $D(\theta,\lambda)$ as crustal thickness at the point with the spherical coordinate of latitude θ and longitude λ and also the Moho surface is smooth enough the spherical harmonic expansion of the crustal thickness is (Heiskanen and Moritz, 1967, p. 29):

$$D(\theta,\lambda) = \sum_{n=0}^{\infty}\sum_{m=-n}^{n} d_{nm} Y_{nm}(\theta,\lambda), \tag{1}$$

where d_{nm} is the fully-normalized spherical harmonic coefficients and it is given by

$$d_{nm} = \frac{1}{4\pi}\iint_{\sigma} D(\theta,\lambda) Y_{nm} d\sigma, \tag{2}$$

σ is the unit sphere and $d\sigma = \sin\theta d\theta d\lambda$ is the surface integration element. $Y_{nm}(\theta,\lambda)$ is the fully-normalized spherical harmonic of degree n and order m (see Heiskanen and Moritz, 1967, Chapter 1 for more details).

In Eq. (1) the data of the crustal thickness are finite and we should replace the notation ∞ with $n_{\max}$ where the Nyquist frequency should be larger than $n_{\max}$ (Colombo, 1981). We know that the Nyquist frequency is obtains from $180^\circ/\Delta$ where Δ is the size of the data on the regular grid. Čadak and Martinec (1991) used the crustal thickness map in a grid with step size 2°. The quality of the seismic data are not uniform and the error of some measurements can affect the results, thus the optimal value of degree n will be smaller than 90. Hence, Čadak and Martinec (1991) presented a simple method to find optimal $n_{\max}$ based on the error of measurement of the quantity. In order to find $n_{\max}$ they introduced the root mean square difference between the data set and fitting model given by the finite spherical harmonic expansion (Čadak and Martinec, 1991):

$$\Delta_{rms} = \left[\frac{1}{2N^2}\sum_{i=1}^{2N^2}\left[D^i - \sum_{n=0}^{n_{\max}}\sum_{m=-n}^{n} d_{nm} Y_{nm}(\theta_i,\lambda_i)\right]^2\right]^{1/2} \tag{3}$$

where index i denotes on number of points (N is number of the points in latitude and number of the points in longitude become $2N$), therefore the data set consists of $2N^2$ values of for $2^\circ \times 2^\circ$ data-set. Δ_{rms} is the root mean square difference between the measured $D(\theta,\lambda)$ and its approximation given by the following harmonic series:

$$D(\theta,\lambda) \cong \sum_{n=0}^{n_{\max}}\sum_{m=-n}^{n} d_{nm} Y_{nm}(\theta,\lambda), \tag{4}$$

Using trial and error method and changing the degree and order it can be obtained different Δ_{rms}. The obtained Δ_{rms} should be compared with a threshold value to estimate $n_{\max}$ based on Eq. (3). Čadak and Martinec (1991) suggested assuming the average