Global secondary indirect effects of topography, bathymetry, ice and sediments

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Abstract: When gravitational effects of density contrasts of various known structural crustal/geologic elements are to be removed from the topographically corrected gravity anomalies, this removal (stripping) consists not only of subtracting the direct effect of these density contrasts, but also of adding the secondary indirect effects of these density contrasts. In this study, we compile global maps of the secondary indirect effects of the topography, of the bathymetry, of ice, and of sediments.

Key words: density contrast, gravimetry, indirect effect, modelling, stripping

1. Introduction

Unlike gravity disturbances, when gravity anomalies are corrected for the gravitational effect of the topography and/or for the effect of density contrasts of known crustal structural elements (such as ice, sediments, ocean saltwater, etc.), the complete gravitational effect consists not only of the direct effect, but also of the secondary indirect effect (e.g., *Vajda et al., 2007*). Gravity anomalies are defined by the fundamental gravimetric equation. The secondary indirect effects owe their origin to the second term of

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the fundamental gravimetric equation. In this paper, we compute the secondary indirect topographical effect (SITE), the secondary indirect bathymetric (ocean saltwater density contrast) effect (SIBE), the secondary indirect ice density contrast effect (SIIE), and the secondary indirect sediment density contrast effect (SISE). The SITE and SIBE are computed globally with a spectral resolution complete to degree 180 using techniques for the spherical harmonic analysis of gravity field. The 2×2 arc-deg global data of ice thickness are used to compute the SIIE with a spectral resolution complete to degree 90, and the 2×2 global data of sediment thickness and density are used to compute the SISE.

2. Global SITE

The 5×5 arc-min global elevation data from ETOPO5 (provided by the NOAA's National Geophysical Data Centre) were used to generate the coefficients of the global elevation model (GEM). These coefficients were then used to compute the SITE with a spectral resolution complete to degree 180 of spherical height functions. We note that the expressions for modeling the topography generated gravitational potential in terms of spherical height functions can be found for instance in *Vaníček et al. (1995)*, and *Novák and Grafarend (2006)*. The SITE was computed at the 1×1 arc-deg geographical grid of points at the Earth's surface. The mean topographic (average crustal) density 2670 kg/m^3 was adopted. The global SITE is shown in Fig. 1. It ranges from 74.2 to 278.4 mGal with the mean of 119.8 mGal, and its variability (in terms of standard deviation) is 36.7 mGal. Due to a correlation of the SITE with the regional topography, its maxima are located in mountainous regions. The minima of the SITE are in central part of the Pacific Ocean.

The inaccuracy of evaluating the long-wavelength SITE for the average crustal density is mainly due to errors within the GEM coefficients. The current accuracy of global digital models ascertains that these errors are small and an accuracy of a few miligals can be achieved in computing the SITE. The density variations within the topography are treated as the stripping corrections and discussed in sections 4 and 5.

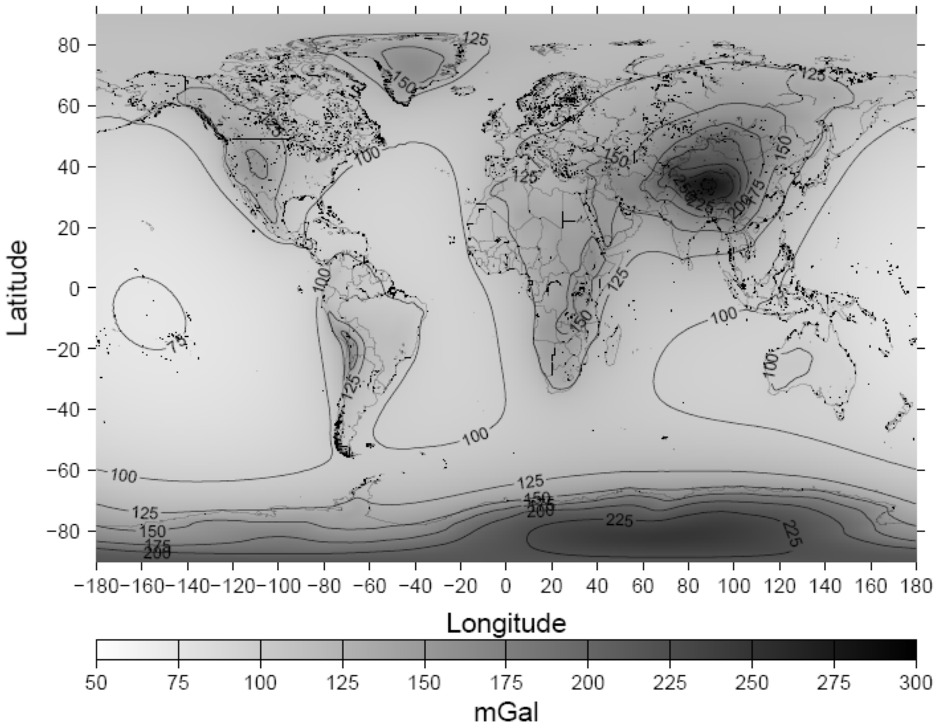

Fig. 1. The global secondary indirect topographic effect at the Earth's surface computed with the spectral resolution complete to degree 180 of spherical height functions. The mean crustal topographical density 2670 kg/m^3 was adopted.

3. Global SIBE

The 5×5 arc-min global bathymetry data from ETOPO5 were used to generate the coefficients of the global bathymetric model (GBM). These coefficients were used to compute the SIBE with a spectral resolution complete to degree 180 of spherical bathymetric functions. The SIBE was computed at the 1×1 arc-deg geographical grid of points at the Earth's surface. The mean value of the ocean density contrast -1640 kg/m^3 (i.e., the difference between the mean ocean saltwater density 1030 kg/m^3 and the average crustal density 2670 kg/m^3) was adopted. The global SIBE is shown in Fig. 2. It ranges from -895.6 to -514.5 mGal with the mean of −702.4 mGal, and the standard deviation is 100.4 mGal. The absolute maxima are located in the central part of the Pacific Ocean. The absolute minima are located in the western part of the central Eurasia.

The actual ocean saltwater density varies (due to salinity, temperature and pressure) from 1020 to 1050 kg/m^3, with most of this range being due to pressure (up to 1.8%). The anomalous ocean saltwater density variations with respect to the mean value 1030 kg/m^3 are thus within the interval from −10 to 20 kg/m^3. The relative errors of modelling the gravitational field generated by the ocean density contrast can then reach 2% at the most. From the error estimation, the approximation of the actual ocean saltwater density by the mean value 1030 kg/m^3 may cause large inaccuracies, particularly at the computation points situated over oceanic areas. The

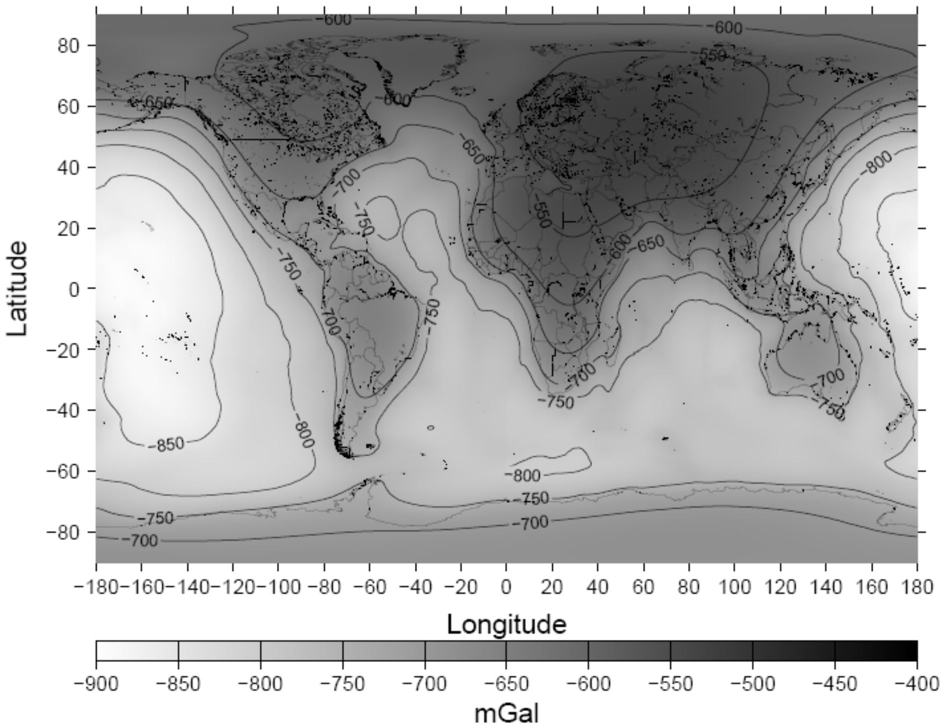

Fig. 2. The global secondary indirect bathymetric effect at the Earth's surface computed with the spectral resolution complete to degree 180 of spherical bathymetric functions. The mean value of the ocean density contrast −1640 kg/m^3 was adopted.

errors of the secondary indirect bathymetric effect up to 18 mGal can be expected. Over continental areas, these errors decrease significantly. For a more accurate computation, the existing oceanographic models of salinity, temperature and pressure (depth) should be facilitated to determine more realistically the ocean saltwater density distribution.

4. Global SIIE

The discrete data of the ice thickness with the 2×2 arc-deg geographical spatial resolution, obtained from the global crustal model CRUST 2.0 (`http://mahi.ucsd.edu/Gabi/rem.dir/crust/crust2.html`), were used to generate the coefficients of the global ice thickness model (GITM). The GITM and GEM coefficients were used to compute the SIIE with a spectral resolution complete to degree 90 of spherical ice thickness functions. The mean value of the ice density contrast -1757 kg/m^3 (i.e., the difference between the mean ice density 913 kg/m^3 and the average crustal density 2670 kg/m^3) was adopted. The global SIIE computed at the 1×1 arc-deg geographical grid of points at the Earth's surface is shown in Fig. 3. It ranges from -109.8 to -10.0 mGal with the mean of -23.3 mGal, and the standard deviation is 23.0 mGal. The absolute maxima correspond to locations of the largest thickness of the polar ice sheet.

Whereas large errors of modelling the gravitational field generated by the ice density contrast are expected in polar areas due to inaccuracies within the currently available global ice-sheet thickness data, errors due to small ice density variations are negligible. Due to the low resolution and expected accuracy of modelling the global secondary indirect effects in this study, the gravitational effect of continental glaciers and water bodies is not considered.

5. Global SISE

The discrete data of the soft and hard sediment thickness and density with the 2×2 arc-deg geographical spatial resolution, obtained from the

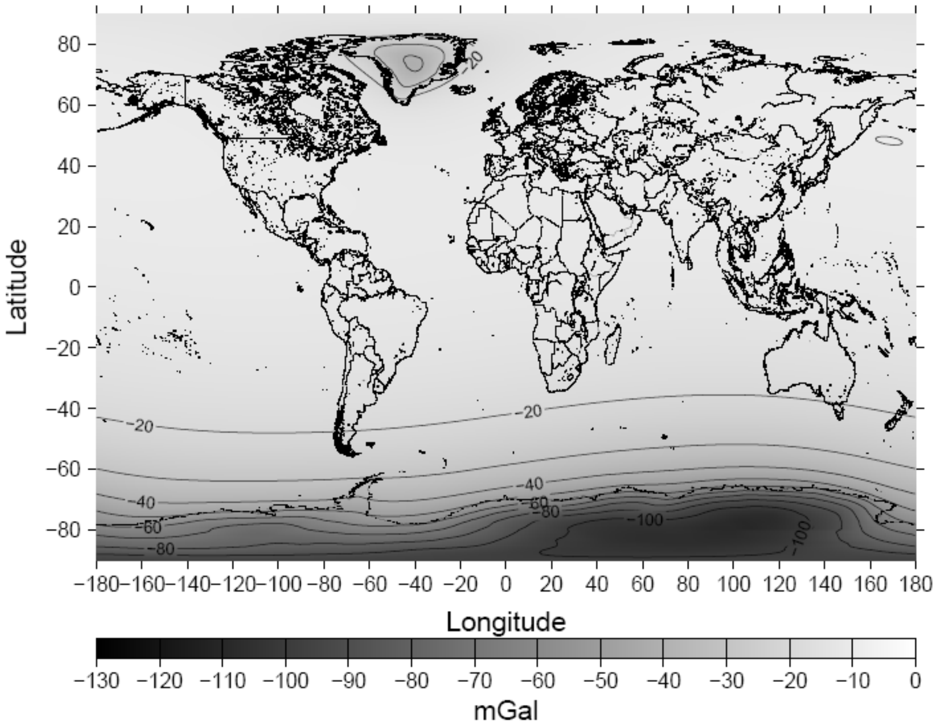

Fig. 3. The global secondary indirect ice density contrast effect at the Earth's surface computed with the spectral resolution complete to degree 90 of spherical ice thickness functions. The mean value of the ice density contrast −1757 kg/m^3 was adopted.

global crustal model CRUST 2.0, were used to compute the SISE. The corresponding values of the sediment density contrasts are defined with respect to the average crustal density 2670 kg/m^3. The global SISE computed at the 1×1 arc-deg geographical grid of points at the Earth's surface is shown in Fig. 4. It ranges from −98.2 to −50.6 mGal with the mean of −70.4 mGal, and the standard deviation is 12.3 Gal. The absolute maxima are mainly located over continental shelves and the Caspian Sea region. The absolute minima are in central part of the Pacific Ocean.

Large errors of modeling the gravitational field generated by the sediment density contrast are expected over areas of the largest sediment density variations within the upper Earth's crust. Another source of errors is due to unmodeled crustal density variations such as a different density of the

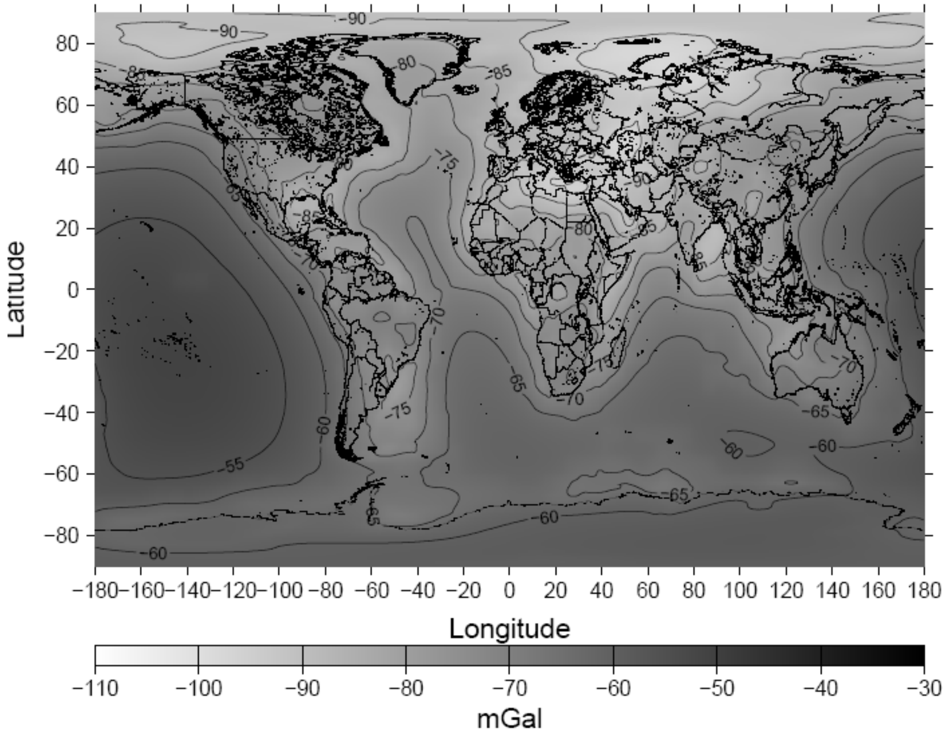

Fig. 4. The global secondary indirect sediment density contrast effect at the Earth's surface computed with the 1×1 arc-deg spatial resolution.

oceanic and continental crust.

6. Summary and conclusions

We have compiled the global maps of the secondary indirect effects. The global secondary indirect topographic effect was computed with a spectral resolution complete to degree 180 of spherical height functions and shown in Fig. 1. The global secondary indirect bathymetric effect was computed with a spectral resolution complete to degree 180 of spherical bathymetric functions and shown in Fig. 2. In Figures 3 and 4, we demonstrated the global secondary indirect effects of the density contrasts (relative to average crustal density) of major anomalous geological structures inside the solid Earth's crust. In particular, we used the 2×2 arc-deg global data of ice thickness to model the secondary indirect ice density contrast effect. The 2×2 arc-deg global data of sediment thickness and density were used to model the secondary indirect sediment density contrast effect. Due to the expected errors and a low-degree spectral resolution used for the global modelling, the effects of continental water and glacier bodies were disregarded.

Large errors are expected in modelling the gravitational field generated by the density contrasts within the solid Earth's crust due to uncertainties about the actual density distribution. Another source of errors is due to inaccuracies of the currently available data about the ice and sediment thickness as well as the stratigrafic data of sediment density. On the other hand, the currently available high-resolution bathymetric data combined with the oceanographic models of salinity and temperature allows an accurate modelling of the gravitational field generated by the ocean density contrast. In this study, we adopted only the mean value of the ocean saltwater density and estimated that this approximation may yield the errors in modelling the secondary indirect bathymetric effect up to 18 mGal. The errors of computing the secondary indirect topographical effect for the average crustal density are expected to be small (at the most up to a few miligals) provided that the coefficients of the global elevation model can be generated very accurately from existing high-resolution and high-accuracy digital terrain models.

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