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Renormalisation of global mantle dynamic topography predictions using residual topography measurements for "normal" oceanic crust

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ABSTRACT

We compare mantle dynamic topography predicted from mantle convection modelling with residual topography measurements for oceanic regions, where crustal basement thickness is 10.0 km or less. Measurements of residual topography, calculated by removing the isostatic effects of crustal thickness variation, bathymetry, sediments, ice and lithosphere thermal anomalies, from the observed topography, are inaccurate for continents and oceanic plateaus due to uncertainties in determining their crustal thickness and density. As a consequence, residual topography measurements for these regions are unsuitable for testing mantle dynamic topography predictions. Residual topography is more accurately determined for oceanic crust. We use global mapping of crustal basement thickness using gravity anomaly inversion to identify oceanic crust of 10.0 km thickness or less to select measured residual topography for comparison with predicted mantle dynamic topography. For these oceanic regions we compare mantle dynamic topography and residual topography and, using amplitude histogram matching and grid searches, compute the amplitude rescaling and shift which needs to be applied to predicted mantle dynamic topography to fit the observed residual topography. We examine three global compilations which use different approaches to determine mantle dynamic topography: (i) Steinberger (2007), which uses seismic topography deeper than 220 km to determine mantle density; (ii) Flament et al. (2013), which uses plate velocity and subduction history; and (iii) Steinberger et al. (2017), which uses seismic tomography, including that above 220 km, to determine shallow upper mantle densities. Our analysis shows that for the Steinberger (2007) and Flament et al. (2013) compilations, the predicted mantle dynamic topography for oceanic regions requires a rescaling of approximately ×0.5 and a negative shift of approximately −500 m to match the observed residual topography. In contrast Steinberger et al. (2017), which includes shallow upper mantle densities above 220 km, requires only a small shift (+50 m) but a greater scaling of ×0.375. Maps of renormalised (rescaled and shifted) mantle dynamic topography for Steinberger et al. (2017) show a close resemblance to measured residual topography.

1. Introduction

Large-scale variations in the Earth's surface topography originate from both changes in crustal and lithosphere thickness, lithosphere temperature structure and composition, and from convective viscous flow within the mantle (e.g. Ricard et al., 1993; Lithgow-Bertelloni and Silver, 1998; Gurnis et al., 2000 and Steinberger, 2016). These two contributions to the support of the Earth's topography have been termed isostatic and mantle dynamic (Allen, 1997). Mantle dynamic topography includes both the consequences of whole-mantle thermal convection resulting in the large scale three-dimensional variations in mantle density, and smaller-scale convection processes associated with mantle plume activity and subduction. The magnitude of mantle dynamic topography is related to the intensity and depth of mantle flow, whilst the wavelength is proportional to the scale and depth of the flow (Richards and Hager, 1984).

Two approaches may be used to examine mantle dynamic topography; (i) predictive forward modelling using 3D mantle convection and (ii) measurement by subtracting the isostatic component of topography from observed topography to give what is often termed residual topography. Within this paper we use the term mantle dynamic topography to refer to present day predictions and residual topography to refer to observations and measurements.

Knowledge of mantle dynamic topography is important, in particular the amplitude and what drives it. Due to its importance, attempts have been made to constrain mantle dynamic topogra-

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phy using observations of its geological pattern, and many authors have used the observations of residual topography to test predictive models of mantle dynamic topography (e.g. Lithgow-Bertelloni and Silver, 1998; Kaban et al., 1999; Gurnis et al., 2000; Panasyuk and Hager, 2000; Flament et al., 2013 and Steinberger et al., 2017).

While at long wavelengths a global comparison of measured residual topography with predicted mantle dynamic topography shows some similarity, significant differences are observed particularly in the Pacific regions where mantle dynamic topography is substantially more positive than residual topography. Many authors (e.g. Watkins and Conrad, 2018; Steinberger et al., 2017; Hoggard et al., 2016 and Yang and Gurnis, 2016) believe that predicted mantle dynamic topography amplitudes are too great when compared to observations of residual topography. Steinberger (2016) suggests that at long wavelengths, corresponding to degree 2, the amplitude of predicted mantle dynamic topography may be twice as large as the observed residual topography. Hoggard et al. (2016) suggest that the power spectrum for predicted mantle dynamic topography at long wavelengths may be an order of magnitude greater than the observed residual topography, while at short wavelengths the opposite occurs with greater amplitudes in the residual topography compared with predicted mantle dynamic topography.

It is therefore important to better constrain the mantle dynamic topography models. Many groups have used observations of residual topography to constrain predictions of mantle dynamic topography. Watkins and Conrad (2018) developed new constraints on the amplitude of long-wavelength mantle dynamic topography by examining asymmetries in seafloor bathymetry across mid-ocean ridges. Steinberger (2016) compares predicted mantle dynamic topography, from a new model incorporating shallow upper mantle density structure, with observations of residual topography, in terms of both correlation and amplitude ratio. Yang and Gurnis (2016) investigated the relationship between free-air gravity and mantle dynamic topography as a function of wavelength and also investigated the possibility that the observed free-air gravity anomalies and the large amplitude long-wavelength mantle dynamic topography can be reconciled. They attempted to verify that at long wavelengths their predicted mantle dynamic topography is consistent with observed residual topography (from Hoggard et al., 2016), in both pattern and amplitude. Steinberger et al. (2017) used the unclear nature of the interpretations of two large, seismically slow regions in the lower mantle beneath Africa and the Pacific oceans (and whether they are large-scale active upwellings or represent collections of regular mantle plumes) to investigate the implications of these upwellings for mantle dynamic topography. In order to do this, they compared their modelled mantle dynamic topography with a new compilation of observed residual topography.

While there is much uncertainty in the model prediction of mantle dynamic topography, there is also uncertainty in the measured residual topography particularly for the continental regions. The calculation of the isostatic topography component for the continents requires knowledge of crustal thickness and density, both of which are uncertain. Similar problems in determining the isostatic correction for topography exist for oceanic plateaus and micro-continents in oceanic regions. Residual topography is more reliably measured in oceanic regions where oceanic crust is of normal or near normal thickness.

In this paper we use an alternative and independent method to compare predicted mantle dynamic topography with observed residual topography. In addition, we produce global maps of renormalised mantle dynamic topography which provide a better fit the measured residual topography. As a strong contribution to the present-day surface topographic signal arises from crustal thickness variations, we restrict the comparison of predicted mantle dynamic topography with residual topography to oceanic regions with normal or near normal crustal thickness where uncertainty in crustal thickness and density are minimised. To achieve this, we use global mapping of crustal thickness, from gravity inversion, to identify normal thickness oceanic crust and avoid oceanic plateaus and micro-continents.

2. Compilations of observed residual topography and predicted mantle dynamic topography examined in this study

We compare mantle dynamic topography with residual topography for three predictive models. These are: Steinberger (2007); Flament et al. (2013); and Steinberger et al. (2017), as shown in Fig. 1. We choose these because they represent distinct approaches for the prediction of mantle dynamic topography.

The Steinberger (2007) model used a mantle convection model following the approach of Hager and O'Connell (1979, 1981). Density distribution within the convection model (below 220 km) was derived from seismic tomography assuming velocity anomalies are the result of temperature variations. The model surface boundary condition used present-day plate velocities from NUVEL (DeMets et al., 1990). The effects of the 660 and 410 km phase transitions were included in the model.

The Flament et al. (2013) model used an approach based on subduction history similar to Ricard et al. (1993). The surface boundary conditions of the mantle convection models used plate velocities for the last 200 Myr derived from Seton et al. (2012) to compute the subduction input into the mantle. In order to suppress the effect of surface traction imposed by plate velocities, the dynamic topography itself is computed with a no-slip surface boundary condition. This modelling methodology only produces the long wavelength components of mantle dynamic topography, in contrast to the approach used by Steinberger (2007) which also produces shorter wavelength components.

The Steinberger et al. (2017) model uses a methodology based on that used in Steinberger (2007) but with additional features. In particular it differs in that it includes the density anomalies derived from tomography above 220 km (as well as those below). For the comparison of predicted mantle dynamic topography and measured residual topography it is important that the residual and mantle dynamic topography models are derived in a mutually consistent manner (e.g. the oceanic lithosphere thermal correction). As a consequence, for the comparison we use the paired grids compilations of mantle dynamic and residual topography, which have been provided by Steinberger and Flament.

The Steinberger (2007) residual topography grids were prepared using an isostatic correction for ocean lithosphere cooling with oceanic ages from Mueller (1997) and an isostatic correction for continental crustal thickness variation using Crust2.0. The Steinberger (2007) residual topography (and mantle dynamic topography) grids are air loaded for both oceans and continents.

For oceanic regions the Flament et al. (2013) residual topography grids were prepared using the plate cooling model of Crosby and McKenzie (2009) and a sediment correction. For continental regions a mean elevation correction was applied rather than a correction for crustal thickness variation. Consequently, the residual topography for the continents (and continental shelves) is likely to be unreliable. The oceanic values are however, more reliable and are used in this study. The Flament et al. (2013) residual topography (and mantle dynamic topography) grids are water loaded for oceans and air loaded for the continents.

For the oceans the Steinberger et al. (2017) residual topography grids were based on the detailed compilation of Hoggard et al. (2016) which were made using corrections for ocean lithosphere