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Short Note **Open Access**

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On the gravity and geoid effects of glacial isostatic adjustment in Fennoscandia - a short note

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Abstract: Many geoscientists argue that there is a gravity low of 10-30 mGal in Fennoscandia as a remaining fingerprint of the last ice age and load, both vanished about 10 kyr ago. However, the extraction of the gravity signal related with Glacial Isostatic Adjustment (GIA) is complicated by the fact that the total gravity field is caused by many significant density distributions in the Earth. Here we recall a methodology originating with A. Bjerhammar 35 years ago, that emphasizes that the present land uplift phenomenon mainly occurs in the region that was covered by the ice cap, and it is highly correlated with the spectral window of degrees 10-22 of the global gravity field, whose lower limit fairly well corresponds to the wavelength that agrees with the size of the region. This implies that, although in principle the GIA is a global phenomenon, the geoid and gravity lows as well as the land upheaval in Fennoscandia are typically regional phenomena that cannot be seen in a global correlation study as it is blurred by many irrelevant gravity signals. It is suggested that a regional multi-regression analysis with a band-limited spectral gravity signal as the observable, a method tested already 2 decades ago, can absorb possible significant disturbing signals, e.g. from topographic and crustal depth variations, and thereby recover the GIA signal.

Keywords: Glacial Isostatic Adjustment, land uplift, postglacial rebound

1 Introduction

The vanishing of the huge ice load over Fennoscandia about 10 kyr before present created a mass deficiency in the Earth's crust and upper mantle that still affects the isostatic balance of the Earth's gravity field and is most obvious in the on-going land uplift, which reaches 1 cm/yr in the Bay of Bothnia [Ekman and Mäkinen (1996); Ågren and Svensson (2007)]. The resulting non-isostatic effect on the gravity field should therefore appear as negative gravity and geoid anomalies. However, as these anomalies are superimposed on the total gravity signals, generated by many kinds of mass heterogeneities in the Earth, they are not directly seen in gravity observations and geoid models. Most important are the long-wavelength effects related with core-mantle topography and mantle convection, as seen in the up-hill slope of the geoid towards the mid-Atlantic ridge. Other disturbances, of shorter wavelengths, are caused, e.g., by the topographic mass and crustal depth variations, the latter not necessarily related with the ice load depression of the crust. Hence, observed gravity is the result of a mixture of many geophysical and geodynamic phenomena, and it is not an easy task to separate the signal related with Glacial Isostatic Adjustment (GIA) from other components. Nevertheless, traditionally this signal has been estimated by various authors to the order of minus 10–30 mGal. However, Anderson (1984) suggested that the observed gravity low is mainly due to crustal thickening, and Marquart (1989), using a numerical study, agreed to Anderson's hypothesis. Sjöberg et al. (1994a) used simple regression analysis to estimate the GIA effects on the geoid and gravity to the orders of −5.5±0.5 m and −21±3 mGal, while the variation of crustal depth has less effects. Using refined data Sjöberg et al. (1994b) estimated the GIA geoid and gravity depressions to −6 m and −28 mGal, while the crustal depth effects were estimated to −5 m and −12 mGal. Recently Kaban et al. (2010) published a "residual mantle gravity map" over Europe, with mostly positive gravity values in Fennoscandia, "leaving no contribution for the GIA gravity signal" according to Root el al. (2015).

Bjerhammar et al. (1980) represented the GIA effect in the region by a band-limited spherical harmonic series of the Earth's gravity field. The harmonic window was selected by a correlation analysis between gravity and land uplift rate, being optimum for the harmonics between 10 and 22, while Sjöberg et al. (1994a) and (1994b) suggested the spectral window 9–22. On the contrary, by comparing the global power spectra of the total gravity field and mod-

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els of the GIA, crust, topography and mantle convection Root et al. (2015) concluded that one cannot select a harmonic window of gravity to isolate GIA, because that signal significantly correlates with the signals from the other models.

Obviously there are still a number of open questions related with using the gravity field in Fennoscandia for studying GIA. In the discussion that follows we address the following related questions:

1. Is the residual mantle gravity map of Kaban et al. (2015) a proof of that static gravity data is not a useful data type?
2. Is (part of) the gravity spectrum a useful tool for GIA studies in Fennoscandia?
3. Does Bjerhammar's method of selecting the optimum harmonic window by correlation analysis make sense?
4. Is the temporal change of gravity a useful observable in determining and/or verifying the possible GIA related geoid and gravity lows?

2 Discussion

Question (a): Theoretically the GIA effect on gravity can be approximated by the signal caused by the elastic depression of an infinite (Bouguer) plate under the ice load, yielding the effect of $-2\pi G\rho_m d \approx -0.17$d [mGal] for depression d in m, where $G$is the gravitational constant, and ρ_m is the density of upper mantle set to 3300 kg/m^3 [see *Question (d)* below]. As the present maximum depression in the Bay of Bothnia is of the order of 80 m (Sjöberg and Bagherbandi 2013), the corresponding GIA gravity low becomes about −10 mGal. So, how does this agree with the positive values in the residual mantle gravity map of Kaban et al. (2010)? Well, the simple answer is that there is no relation between the two features, and that is because the GIA gravity signal is generated in the upper crust and crust/mantle boundaries, which signals are removed in the residual mantle gravity anomaly. As stated by M. Kaban (private communication.): "Definitely the residual mantle gravity anomalies, which we calculate since 1992 by removing the crustal effects, have no relation to GIA."

On the other hand Balling (1980) and Root et al. (2015) proposed that the GIA gravity signal will be visible when an isostatic correction is performed. However, this information is not needed in the linear regression technique with topographic height as one parameter. This is because, in practice, the isostatic contribution to the geoid height (based on either Airy's or Pratt's model) is linearly related with topographic height (see Turcotte and Schubert 2005; p. 219), so that the unknown parameter in the adjustment related with topography absorbs the topographic/isostatic effect.

Question (b): Fig. 9 in Root et al. (2015) shows that the spectra of gravity signals from topography, crust and mantle convection overlaps with the GIA signal. However, this figure shows the global spectra, which do not prove that the signals overlap significantly in Fennoscandia. That is, one must distinguish between global and regional correlation of signals. For example, Sjöberg (1983) concluded that there is no significant global correlation between the gravity field and the Fennoscandia GIA phenomenon, but he emphasized that the regional correlation is of the order of −0.9 or more. (Actually, the studies by Bjerhammar and later by Sjöberg et al. were all based on regional data from Fennoscandia). One may also expect that mantle convection, the most powerful signal in the figure of Root et al. (ibid.), is not very significant under the stable Fennoscandia bedrock shield. Nevertheless, also when limiting the data to the region one could expect significant contributions from the crust and topography, and for precise analysis these effects should be removed from the total signal in one way or another.

Question c): The approach by Bjerhammar and colleagues at Royal Institute of Technology (KTH) in Stockholm was based on finding the optimum harmonic window of the gravity spectrum with maximum correlation with the land uplift rate in the region. In this way a very significant correlation could be reached for the spectral window 10–22. Bjerhammar regarded GIA as the only cause of this gravity signal, but, as stated in (*b*) it is likely that other contributors play a role and should be considered as well. Therefore, simple regression analysis is one way to separate the various causes to the total gravity low (e.g., Sjöberg et al. 1994a). However, Root et al. (2015) found that "the crustal anomalies cannot be effectively removed because of uncertainties in the crustal and upper mantle density models". This is true, but even with 10–20 % uncertainty in the crustal density the regression analysis would perform pretty well.

Question (d): The ratio between the observed land uplift rate and the repeated gravity observations in the region was estimated to −0.162 ± 0.038 µGal/mm by Sjöberg (1990) and to −0.204 ± 0.058 by Ekman and Mäkinen (1996) based on repeated relative gravimeter observations. Recent analyses of repeated absolute gravity measurements and GPS data (Gitlein 2010) gave the more precise ratio −0.167 ± 0.004 µGal/mm, suggestion a viscous inflow of mantle mass below the crust with a density of the order of 3300 kg/m^3 along with the uplift. The estimated density in the GIA mantle flow is important, e.g. in estimating the remaining uplift from the geoid low and vice versa (Ekman and Mäkinen 1996; Sjöberg and Bagherbandi 2013).

3 Concluding remarks

There is a regional gravity low over Fennoscandia caused by the previous ice load that disappeared about 10 kyr ago, and the on-going land uplift is a GIA phenomenon, whose uplift rate-to-gravity change agrees with a viscous flow of upper mantle material to compensate for the uplifting crust. The main problem discussed here is whether the gravity signal related with GIA can be extracted from the total gravity signal in the region. The KTH method starts by finding the spectral window the global gravity field that best correlates regionally (and not globally) with the land uplift rate. As a second step the band-limited harmonic representation of the gravity or rather geoid signal is analysed by multilinear regression for models of land uplift rate (assumed generated by the GIA), crustal depth and possibly also other parameters such as topography and mantle convection. This process distributes the observed geoid signal among the causing signals, and the least squares fit of the model is a measure of the success. In this process crustal and topographic gravity models with uncertainties, say, within 10–20% should not be very harmful for the result. If the fit is bad other causes could be included and the regression could be augmented to include also quadratic terms. Although some preliminary studies along this line were performed already 20 years ago, more research, including today's improved data, is needed to explore the advantages and disadvantages of the technique.

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