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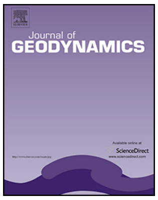

Absolute gravity observations in Norway (1993–2014) for glacial isostatic adjustment studies: The influence of gravitational loading effects on secular gravity trends

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ABSTRACT

We have compiled and analyzed FG5 absolute gravity observations between 1993 and 2014 at 21 gravity sites in Norway, and explore to what extent these observations are applicable for glacial isostatic adjustment (GIA) studies. Where available, raw gravity observations are consistently reprocessed. Furthermore, refined gravitational corrections due to ocean tide loading and non-tidal ocean loading, as well as atmospheric and global hydrological mass variations are computed. Secular gravity trends are computed using both standard and refined corrections and subsequently compared with modeled gravity rates based on a GIA model. We find that the refined gravitational corrections mainly improve rates where GIA, according to model results, is not the dominating signal. Consequently, these rates may still be considered unreliable for constraining GIA models, which we trace to continued lack of a correction for the effect of local hydrology, shortcomings in our refined modeling of gravitational effects, and scarcity of observations. Finally, a subset of standard and refined gravity rates mainly reflecting GIA is used to estimate ratios between gravity and height rates of change by ordinary and weighted linear regression. Relations based on both standard and refined gravity rates are within the uncertainty of a recent modeled result.

1. Introduction

Gravimetry considers the observation or measurement of gravity. It may be spaceborne, air- and shipborne, or ground-based (terrestrial), where latter observations may be used to validate results from the first (e.g., Šprlák et al., 2015). Observing temporal gravity changes, and thus changes in the Earth's density distribution, gives insight into a range of geophysical phenomena, e.g., Earth tides, Chandler wobble, core, mantle and tectonic processes (Torge and Müller, 2012), sea-level change (e.g., Simpson et al., 2013), the hydrological cycle (e.g., Pálinkáš et al., 2012), and cryospheric mass variations (e.g., Breili and Rolstad, 2009; Arneitz et al., 2013). Long-term temporal gravity changes can be observed by repeated absolute gravimetry, with an accuracy of $\sim 0.5\,\mu\text{Gal}\,\text{yr}^{-1}$ (where $1\,\mu\text{Gal} = 10^{-8}\,\text{ms}^{-2}$) after 10 years of annual observations (Van Camp et al., 2016).

As opposed to space-geodetic observation techniques such as Global Navigation Satellite Systems (GNSS), absolute gravity (AG) is independent of the terrestrial reference frame, and may thus be used to assess it (e.g., Mazzotti et al., 2011; Collilieux et al., 2014). Furthermore, AG is particularly suitable for monitoring long-term vertical deformation (Van Camp et al., 2011) caused by, e.g., glacial isostatic adjustment (GIA) in North America (e.g., Lambert et al., 2006) and Fennoscandia (e.g., Steffen et al., 2009; Pettersen, 2011; Müller et al., 2012; Timmen et al., 2011, 2015; Nordman et al., 2014), alongside GNSS (e.g., Milne et al., 2001; Vestøl, 2006).

Sasagawa (1989) reviewed the required time span of gravity observations for determining a secular gravity trend with desired accuracy, given by

$$\sigma_{\dot{g}} = \frac{\sigma_g \sqrt{12}}{T\sqrt{N - \frac{1}{N}}}, \tag{1}$$

where $\sigma_{\dot{g}}$ is the trend uncertainty, σ_g is the uncertainty of individual gravity observations, T is the time in years, and N the number of observations. Eq. (1) assumes evenly distributed observations with known uncertainties and a true Gaussian distribution. Steffen

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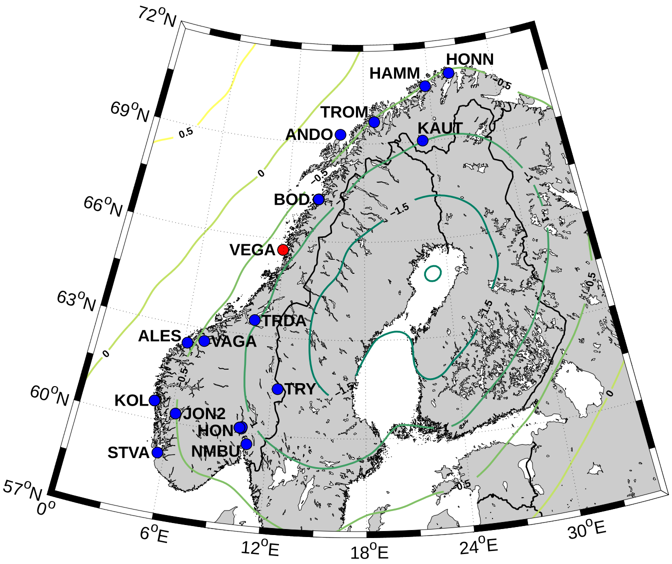

Fig. 1. AG sites in Norway. Blue sites have been observed more than once. The contour lines show modeled gravity rates ($\mu\text{Gal yr}^{-1}$) from the preliminary NKG2016GIA_prel0306 GIA model (H. Steffen, personal communication, 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and Wu (2011) further state that a secular gravity trend should be known within an uncertainty of $\pm 0.5\,\mu\text{Gal yr}^{-1}$ for crustal deformation studies, which, by Eq. (1), should be achieved by five to six years of annual gravity observations with $\sigma_g \approx 1-2\,\mu\text{Gal}$.

In 1990, the Nordic Geodetic Commission (NKG, http://www.nordicgeodeticcommission.com/) began establishing a geodetic network for monitoring crustal deformations and sea-level changes in Fennoscandia and Svalbard. As part of this initiative, the first AG observations with modern instruments were performed in Norway in 1991 and 1992 (Roland, 1998). Between 1991-1995, several AG campaigns were conducted in Fennoscandia and Svalbard (Roland, 1998).

Breili et al. (2010) established an AG reference frame for Norway including 16 gravity sites. Since then, it has been extended to include 21 sites, as shown in Fig. 1 and Table 1. Gravity sites marked in blue have been observed more than once, thus only VEGA is excluded from the set of candidates for trend computation. There exist single observations at a few other sites, but these are less likely to be revisited and are therefore not considered in our work. The observation time spans are $\sim$5 years or longer for 18 of the 21 sites (Table 1). Unfortunately, some gravity sites show uneven observation distributions, with typically larger gaps between initial and later observations. Thus we interpret Eq. (1) as a best-case scenario for our data sets.

The present crustal movements of Fennoscandia are largely due to the viscoelastic process of GIA (or postglacial rebound), which has been monitored by geodetic techniques (e.g., Milne et al., 2001; Lidberg et al., 2010; Kierulf et al., 2014; Steffen and Wu, 2011). The GIA pattern of Fennoscandia is shown in Fig. 1.

This work presents results from two decades of AG observations in Norway, and an attempt is made to derive empirical secular gravity trends based on these data. Our main goal is to explore to what extent the gravity trends are applicable for GIA studies. A prerequisite for this goal is a homogenization of the gravity trends through a consistent analysis of the AG data. This is done by investigating to what extent the gravity trends reflect GIA or other geophysical processes. Ideally, careful reduction of other geophysical processes will ultimately give the pure GIA signal. Therefore, we compute refined ocean loading, atmospheric, and global hydrological effects on gravity, and explore how these affect the trends. Finally, the relation between gravity and height rates of change is investigated. The presented gravity values serve as a Norwegian contribution to the Fennoscandian AG project of the Working Group on Geodynamics of the NKG, which aims to combine all Fennoscandian AG data in a joint analysis on postglacial gravity change for the region.

Section 2 covers fundamentals of the AG processing scheme, where Sections 2.1 and 2.2 concern the refined modeling of ocean, atmospheric and hydrological effects on gravity. Secular gravity trends are computed in Section 3, and a subset of reliable trends are used for determining ratios between the rates of change of gravity and height. Results are discussed in Section 4, while Section 5 concludes the work with recommendations for future AG observations in Norway.

2. Processing absolute gravity

All AG observations in this work were made with the FG5 (Niebauer et al., 1995) absolute gravimeter, which has an accuracy of 1–2 μGal. It is ballistic, i.e., it applies the free-fall principle, where a test mass is dropped in vacuum. A laser interferometer and atomic clock are used to obtain time-distance pairs, and Newton's equations of motion are solved to obtain the acceleration. A typical observation campaign lasts 1–2 days, including several hourly gravity sets where a set consists of 50-100 drops of the test mass. With few exceptions, we have used observations made during the same season (between May and September), so as to reduce seasonal effects (e.g., the influence of surface snow cover during winter).

To minimize computational biases, we have adopted a common processing scheme for the data analysis, ensuring consistency with respect to model and setup parameters. All raw gravity observations have been reprocessed using the g9 software (Micro-g LaCoste, 2012), developed by Micro-g LaCoste and bundled with the instrument.

Vertical transfer of the measured gravity value is done using the vertical gravity gradient, which has been determined at each gravity site using the LaCoste & Romberg G-761 relative gravimeter, see Table 1. All AG observations in this work are given at a reference height of 120 cm, close to a point where the influence of the gradient uncertainty on the FG5 is almost zero (Timmen, 2010).

The most important time-variable components of the raw gravity value are reduced in the software by various models, i.e., variations due to solid Earth and ocean tides, polar motion, ocean loading, and atmospheric mass (Timmen, 2010). The atmospheric correction is determined by observed barometric pressure during the observations, which was done at all sites except Hammerfest in 2006.488, where the barometer failed, and pressure observations transferred from a nearby weather station were used instead (Breili et al., 2010). Corrections for polar motion were computed using final polar coordinates from the International Earth Rotation and Reference Systems Service (IERS), at http://datacenter.iers.org.

The bulk of observations presented here were made with the FG5-226 AG meter of the Norwegian University of Life Sciences (NMBU). The rubidium (Rb) frequency standard of the FG5-226 has been calibrated (i.e., compared with a stable reference signal) at convenience since its acquisition in April 2004, and on a regular basis using a portable Rb reference since the oscillator was replaced in May 2007. We have observed it to vary within a range of $\sim$0.02 Hz (where 0.01 Hz roughly corresponds to 2 μGal). While Gitlein (2009) reports a linear drift of the FG5-220 Rb frequency, the FG5-226 Rb frequency development is non-linear, see Fig. 2. A stable frequency was observed with the original oscillator, while the frequency changed by ~ -0.005 Hz during the first year after its replacement. Then it was stable within 0.002 Hz until a large

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