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Journal of Geodynamics 41 (2006) 227–233
JOURNAL OF GEODYNAMICS
http://www.elsevier.com/locate/jog

Study of the seasonal gravity signal in superconducting gravimeter data

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Accepted 30 August 2005

Abstract

Thanks to their high sensitivity and their long-term stability, superconducting gravimeters (SG) are able to record surface gravity changes on a wide frequency band (periods from a few seconds to secular variations). We focus in this presentation on the seasonal gravity changes measured by about 20 worldwide SG. We model all well-known sources of long-term gravity changes, i.e. solid Earth tides, polar motion and length-of-day as well as global atmospheric, tidal and non-tidal ocean loading effects. These corrections lead to gravity residuals characterized by a strong seasonal signal with an amplitude of a few microgals. We compare these residuals with loading estimates from global hydrology (snow and soil-moisture) models. For more than half of the analysed SG, we are able to show a good correlation between the gravity residuals and the estimated continental water storage loading effects. For the other instruments, the discrepancies may be associated with local hydrology effects, which cannot be taken into account in global continental water storage models.

Keywords: Superconducting gravimeters; Continental water storage; Hydrology loading

1. Introduction

Most of geodetic observations show large annual or seasonal variations which are most likely due to changes of continental water storage. A review of environmental loading effects on geodetic measurements can be found, for example, in van Dam and Wahr (1998). Dong et al. (2002) studied large scale seasonal deformation with worldwide GPS stations. Our goal is to perform a similar study on gravity changes measured by superconducting gravimeters (SG). van Dam et al. (2001) have computed the induced gravity changes due to soil-moisture and snow loading for most of the GGP (Global Geodynamics Project, Crossley et al., 1999) sites. However they did not compare their model to gravity observations; we propose here to compute this loading using two different hydrology models, and to compare it with SG observations. We are presenting in Section 2 the processing of gravity data as well as our models of long-period gravity changes, including the estimate of their precision. We discuss our results in Section 3. Concluding remarks are given in Section 4.

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doi:10.1016/j.jog.2005.08.035

2. Modelling seasonal gravity changes

The 1 min gravity and pressure data of 17 different SG, downloaded from the GGP database (http://ggp.gfz-potsdam.de/), are first corrected for major instrumental perturbations such as gaps, spikes or offsets following the classical procedure (Crossley et al., 1993) and are decimated to a daily sampling using a low-pass filter with a cut-off frequency of 0.33 cycle per day.

In order to get the observed seasonal gravity variations induced by continental water storage changes, the filtered gravity has to be corrected for all other contributions. At seasonal timescales the major sources of gravity changes are (see, for example, van Dam and Wahr, 1998):

- solid Earth tides and ocean tidal loading,
- pole tide (polar motion and length-of-day variations) and its ocean response,
- atmospheric loading,
- non-tidal ocean loading,
- continental water storage (soil-moisture, snow, lakes, etc.) loading.

We describe in the following paragraphs how we modelled all these contributions. As we filtered the observed gravity, we only model gravity changes for periods larger than 3 days.

2.1. Solid Earth tides and ocean tidal loading

The solid Earth tides are modelled using Dehant et al. (1999) Love numbers and Hartmann and Wenzel (1995) tidal potential; only the long-period waves are considered in this computation. The long-period ocean tidal loading is computed from NAO99b (Matsumoto et al., 2000; Takanezawa et al., 2001) zonal tide model.

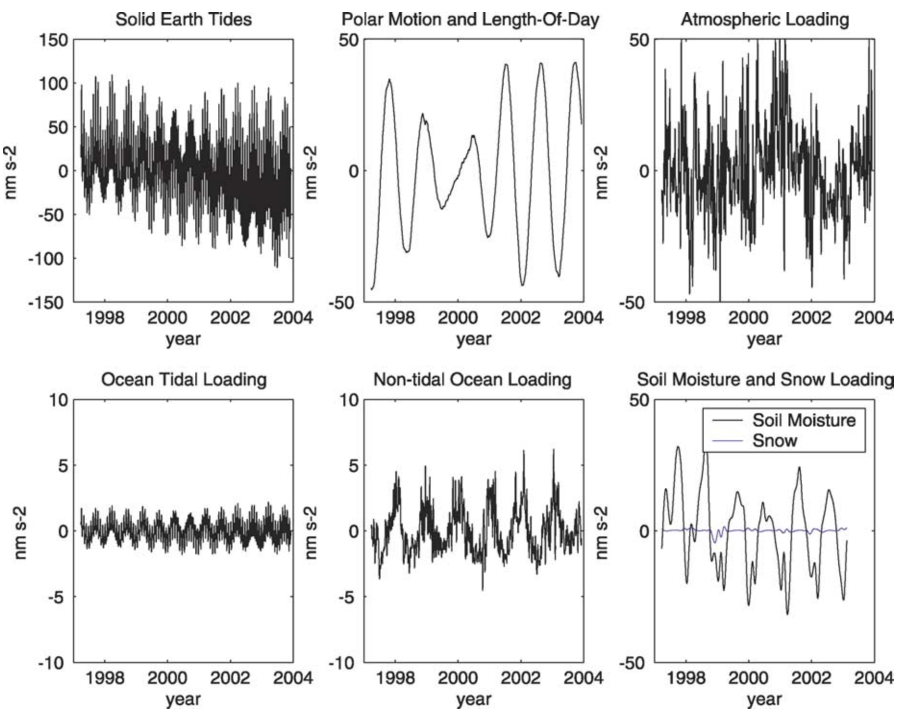

Fig. 1. Modelled contributions to seasonal gravity changes at Strasbourg. Only the long-periods tides are considered here, the amplitude of the solid Earth tides and the ocean tidal loading would be 10 times larger otherwise.

2.2. Pole tide

The pole tide, induced by polar motion and length-of-day variations, is modelled using daily Earth orientation parameters provided by the International Earth Rotation Service (EOPC04 series). The gravimetric factor is supposed to be equal to 1.16 (no frequency or latitude dependence). As we are looking at seasonal timescales, we can assume that the ocean response is static (Agnew and Farrell, 1978). In any case the ocean pole tide loading does not exceed 5% of the solid Earth contribution for all SG.

2.3. Atmospheric loading

The atmospheric loading is modelled using NCEP (National Centers for Environmental Prediction) Reanalysis (Kalnay et al., 1996) surface pressure fields, following Boy et al. (2002). Because we are looking at seasonal timescales, we can assume that the oceans are responding to atmospheric pressure changes as an inverted barometer (see, for example, Wunsch and Stammer, 1997). We are not considering the three-dimensional attraction of air masses, which can lead to differences between our two-dimensional loading of the order of a microgal ($10\,\mathrm{nm\,s^{-2}}$) at seasonal timescales (Simon, 2002; Neumeyer et al., 2004).

2.4. Non-tidal ocean loading

We modelled the non-tidal oceanic contribution to gravity changes using bottom pressure outputs (http://ecco.jpl.nasa.gov/) from the ECCO (Estimating the Circulation and the Climate of the Ocean) general circulation model. This state-of-the-art circulation model is also improved by assimilating altimetry, surface temperature and XBT data.

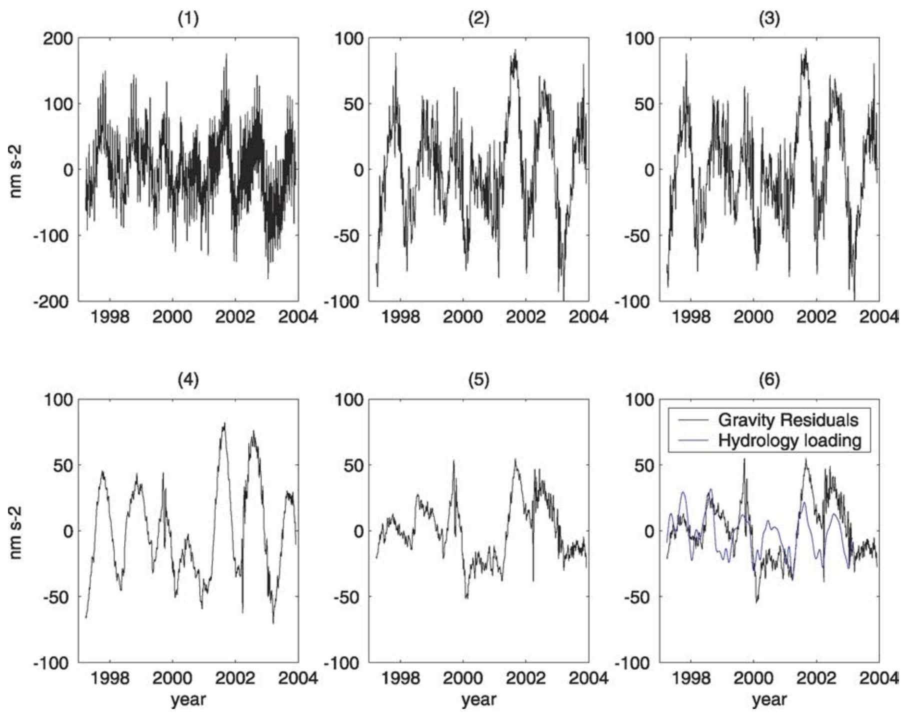

Fig. 2. Gravity residuals after successive corrections. (1) Observed gravity changes; (2) after solid Earth tides removal; (3) after solid Earth and ocean tidal loading correction; (4) after tidal and atmospheric loading corrections; (5) after tidal, atmospheric and polar motion removals; (6) gravity corrected for all above corrections and modelled hydrology loading from LaD model (soil-moisture and snow).

2.5. Continental water storage loading

We modelled the hydrological gravity contributions with two different global models: the LaD (Land Dynamics) model developed by Milly and Shmakin (2002) with spatial and temporal sampling of 1° and 1 month, and the GLDAS (Global Land Data Assimilation System) model (Rodell et al., 2004) with the same spatial sampling but given every 3 h. The outputs consist in soil-moisture content as well as equivalent snow thickness. We modelled the loading as a thin-layer process acting on a spherical Earth surface; another important parameter for modelling the direct Newtonian attraction is the sign of the local contribution: if the station is buried in the ground, a excess of water mass will decrease the gravity (case of Membach or Strasbourg, for example) and the opposite if the station is located at the surface (Medicina or Cantley, for example).

Fig. 1 shows all these modelled gravity contributions for the mid-latitude station of Strasbourg. At higher latitude, the amplitudes of the solid Earth tides and ocean tidal loading are larger; they reach respectively 250 and 7.5 nm s^{-2} for Ny-Alesund in Svalbard.

A rough estimate of the precision of all loading contributions (except the hydrology loading) gives a value of about 10 nm s^{-2} as an upper limit: the solid Earth tides and the pole tide are known to about 1% (differences between the elastic and the inelastic Love numbers in Dehant et al., 1999), i.e. a few nm s^{-2}, the tidal and non-tidal ocean loading are usually below 10 nm s^{-2}, and we can assume they are known with a precision less than 10%. The atmospheric loading is modelled using only the surface pressure, therefore we neglected the effects induced by changes of the vertical density profiles, which can lead to errors of the order of 10 nm s^{-2} (Neumeyer et al., 2004).

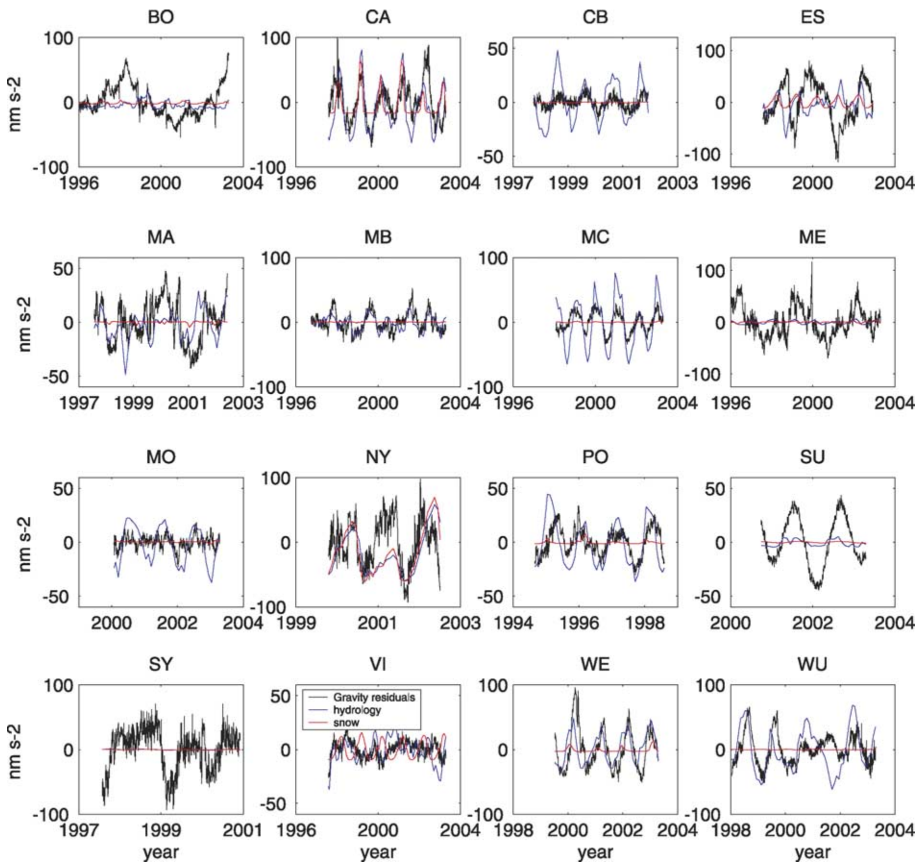

Fig. 3. Gravity residuals for most SG data and hydrological loading computed from LaD model. BO: Boulder (USA), CA: Cantley (Canada), CB: Canberra (Australia), ES: Esashi (Japan), MA: Matsushiro (Japan), MB: Membach (Belgium), MC: Medicina (Italy), ME: Metsahovi (Finland), MO: Moxa (Germany), NY: Ny-Alesund (Svalbard), PO: Potsdam (Germany), SU: Sutherland (South Africa), SY: Syowa (Antarctica), VI: Vienna (Austria), WE: Wettzell (Germany) and WU: Wuhan (China).

Fig. 2 shows the gravity residuals after each correction, for the Strasbourg instrument. The last plot corresponds to the gravity residuals corrected for all modelled gravity contribution (except hydrology loading) superimposed with the modelled hydrology loading (soil-moisture and snow) from LaD model (Milly and Shmakin, 2002).

3. Discussion

Fig. 3 gives the gravity residuals and the soil-moisture and snow loading derived from LaD (Milly and Shmakin, 2002) model. For most of the stations, there is a quite good agreement (both in amplitude and phase) between the gravity residuals and the modelled hydrology contributions, at the microgal (10 nm s^{-2}) level (the precision of other gravity corrections). As the soil-moisture and snow is not correctly modelled in case of permanent ice regions in most hydrology models, we had to remove all regions of permanent ice coverage (Antarctica, Greenland, etc.), therefore the loading in Syowa cannot be coherent with gravity observations. For Boulder (Colorado, USA), the two Japanese stations (Esashi and Matsushiro), Metsahovi, Vienna and Moxa in Europe, the gravity residuals are not correlated with the estimated hydrology contribution; this may be due to some local effects (see, Kroner et al., 2004; van Dam and Francis, 1998) or the poor spatial resolution (1°) for islands like Japan. For Canberra (Australia) and Medicina (Italy), there is a quite good correlation between the loading and the residuals (see Fig. 4); however there is a strong mismatch in amplitude. It is also interesting to note that the hydrology contribution is quite coherent all over Europe (van Dam et al., 2001; Andersen and Hinderer, 2005; Crossley et al., 2005; Hinderer et al., 2006), except with some sign changes, due to the relative position of the instruments with respect to the ground (see Section 2.5).

Fig. 5 shows, for some stations, the gravity residuals and the estimated soil-moisture and snow loading effects with the LaD (Milly and Shmakin, 2002) and GLDAS (Rodell et al., 2004) models. Despite the shorter length, and the different sampling rate (1 month and 3 h), the seasonal signal agrees quite well, especially in phase. It is also interesting to note that some of the short-term gravity changes are coherent with the high frequency hydrology (see, for example, 2003.5–2004.0 for Cantley), suggesting that hydrology also plays a role for sub-seasonal gravity changes.

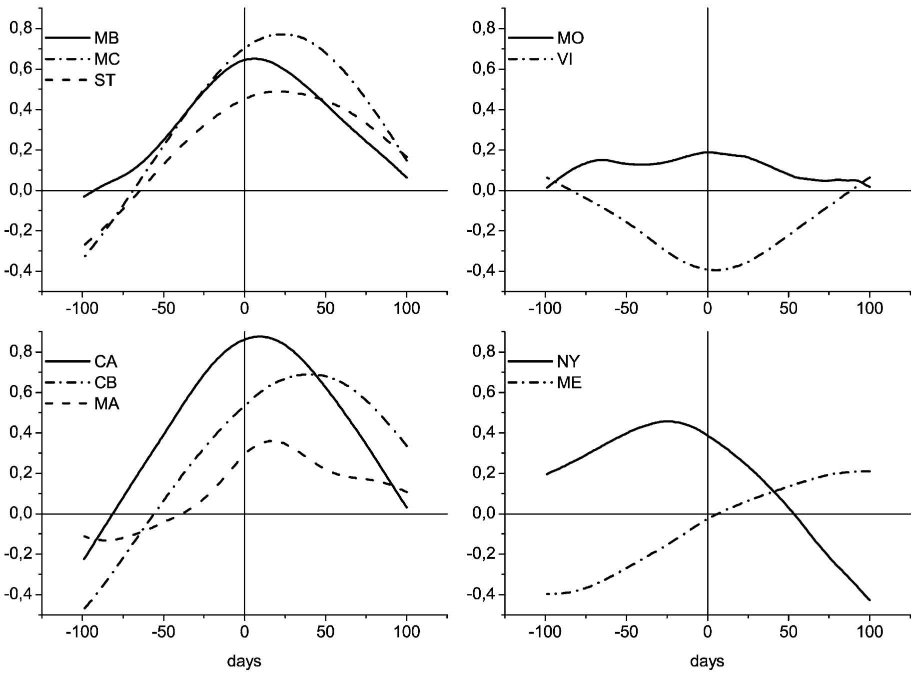

Fig. 4. Correlation between gravity residuals and hydrology loading computed from LaD model.

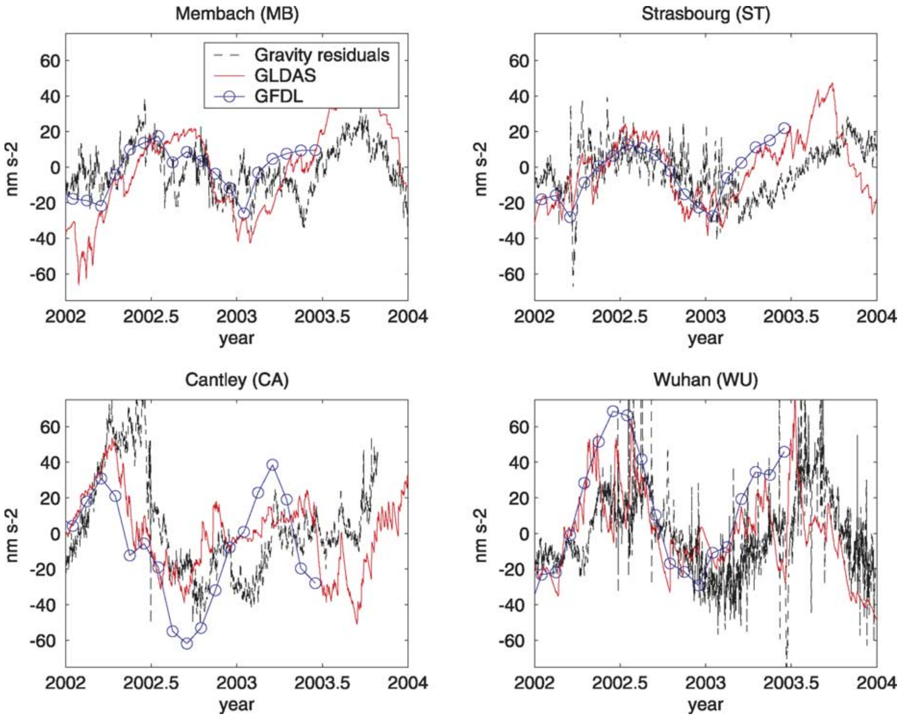

Fig. 5. Comparison of LaD (Milly and Shmakin, 2002) and GLDAS (Rodell et al., 2004) derived gravity changes for Membach, Strasbourg, Cantley and Wuhan.

4. Conclusion

We have shown that the contribution of the continental water storage changes (soil-moisture and snow) to gravity variations is one of the largest at seasonal timescales. For more than half of the studied SG, we have been able to show a strong correlation between gravity observations and the modelled loading using outputs for global hydrology models.

However there are still large discrepancies in amplitude between the modelled loading and gravity variations for some SG. In order to improve our loading estimates, we need to take into account the local or regional hydrology (the global models have only a resolution of 1°), as well as a precise topography for computing the direct attraction by nearby water masses. We have also to better model the atmospheric contributions to gravity changes, by modelling the three-dimensional attraction of air masses in the neighbourhood of the gravimeters. The expected differences with our two-dimensional loading may reach amplitudes of about 1 microgal at seasonal timescales.

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