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Estimation of local water storage change by space- and ground-based gravimetry

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ABSTRACT

We estimated local water storage change by combining space- and ground-based gravimetry in this paper. The gravity change from GRACE was first divided into local and global parts according to potential theory. We then subtracted the GRACE-derived global field from ground gravimeter results to obtain local gravity change which is directly induced by the local water storage. Finally we inferred the local water storage change. We used superconducting gravimeter (SG) data recorded from June 2008 to June 2012 at Wuhan station and GRACE satellite gravimetric data to estimate the local water storage change. To validate the inferred local water storage change, the water table records of a well which is several meters away from SG station were compared. Furthermore, the equivalent water heights from hydrological models and GRACE were used also for comparisons. The comparisons show that the results from combining SG and GRACE data are better than those from either GRACE data alone or hydrological models, which demonstrates the efficiency of the combination method to derive local water storage.

1. Introduction

The launch of the twin satellites of gravity recovery and climate experiment mission (GRACE) provided us monthly time-variable gravity field of the Earth with unprecedented precision (Tapley et al., 2004). The products of this mission are now widely applied in geodesy and geophysics (Ramillien et al., 2004; Han et al., 2006; Chen et al., 2007; Pfeffer et al., 2011; Crossley et al., 2012). Specifically, it allows us to evaluate the water transportation. However, due to the large errors in the GRACE-recovered gravity field of the high degrees' spherical harmonics, some special techniques such as Gaussian smoothing should be applied to avoid the south–north stripes. Therefore only a certain resolution of water distribution, e.g. 300 km, can be accurately determined after smoothing. Therefore, GRACE does well in estimating global or regional water storage change but not in estimating local one.

On the other hand, the superconducting gravimeter is a type of relative gravimeter with high precision and high stability. It can detect gravity change in 0.1 μgal (1 μgal $= 10^{-8}$ m/s^2) and has a low drift which is about several μgal per year (Xu et al., 2008). More importantly, the gravity change from SG is measured at a point on the Earth's surface. Consequently, it contains abundant signals due to local environmental effects, including hydrological one. However, we can't obtain the information on the local water storage by using SG data alone. Therefore another data need to be combined, e.g. GRACE data.

Nevertheless, the gravity changes obtained from GRACE and SG are not comparable because, unlike SG, GRACE satellites can't sensor the vertical displacement of the Earth's surface. Fortunately, the hydrological effect has a dominant seasonal period while almost only the hydrological effect is left in the GRACE result in this period after removing tidal and atmospheric effects. Therefore, Neumeyer et al. (2006) developed an approach to make the two gravity changes comparable by considering the water loading effect on the vertical displacement of the Earth's surface. However, a factor of $1 + k'_n$ was not taken into account in this term, in which k'_n is the load Love number corresponding to additional potential (Farrell, 1972). Hence a correction was made on the formula (de Linage, 2008; Zhou et al., 2009).

Now that the gravity changes from GRACE and SG are comparable, we can isolate the local water storage by combining these two kinds of gravimetric data. Section 2 gives the rationale of how to combine GRACE and SG data to estimate local water storage and Appendix A gives the accessory knowledge of the potential theory. Section 3 introduces the data used and the processing procedures of these data and shows an application of the theory and the consequent results and discussions. And finally some conclusions are drawn in Section 4.

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2. Rationale

2.1. Space- and ground-based gravity changes

The geopotential of the Earth can be represented by the spherical harmonics as

$$T(r,\theta,\lambda)=\frac{GM}{R}\sum_{n=0}^{\infty}\left(\frac{R}{r}\right)^{n+1}\sum_{m=0}^{n}\left[\overline{C}_{nm}\cos(m\lambda)+\overline{S}_{nm}\sin(m\lambda)\right]\overline{P}_{nm}(\cos\theta) \tag{1}$$

where T is the geopotential of the Earth, r is the distance from the point of interest to the Earth's center, θ and λ are co-latitude and longitude of the point of interest, respectively, G is the gravitational constant, M is the mass of the Earth, R is the radius of the Earth, $\overline{C}_{nm}$ and $\overline{S}_{nm}$ are the fully normalized spherical harmonic coefficients, i.e., Stokes coefficients, which are provided by GRACE products, $\overline{P}_{nm}$ is the fully normalized associated Legendre function, n and m are, the harmonic degree and order, respectively.

The gravity change on the Earth's surface can be derived from GRACE products according to (de Linage, 2008; Zhou et al., 2009)

$$\Delta g^S(R,\theta,\lambda)=-\frac{GM}{R^2}\sum_{n=0}^{\infty}\left(n+1-\frac{2h_n'}{1+k_n'}\right)\sum_{m=0}^{n}\left[\overline{C}_{nm}\cos(m\lambda)+\overline{S}_{nm}\sin(m\lambda)\right]\overline{P}_{nm}(\cos\theta) \tag{2}$$

in which Δg^S denotes space-based gravity change on the Earth's surface, h_n' and k_n' denote the load Love numbers of degree n for vertical displacement and potential, respectively. However, due to the large errors in the high-degree Stokes coefficients provided by GRACE products, a filter is usually applied, for example Gaussian filter (Whar et al., 1998), to obtain a reliable result.

On the other hand, the gravity change on the Earth's surface can be measured directly by ground instruments such as superconducting gravimeter. We denote this change by Δg^G. Theoretically, the gravity changes on the Earth's surface derived from space and ground-based techniques are identical.

2.2. Water storage change

From the Stokes coefficients, we can derive the equivalent water height which can also be expanded in spherical harmonics, i.e.

$$H(\theta,\lambda)=R\sum_{n=0}^{\infty}\sum_{m=0}^{n}\left[\overline{C}^H_{nm}\cos(m\lambda)+\overline{S}^H_{nm}\sin(m\lambda)\right]\overline{P}_{nm}(\cos\theta) \tag{3}$$

The coefficients can be derived from gravity field according to the relation below (Whar et al., 1998)

$$\begin{pmatrix}\overline{C}^H_{nm}\\ \overline{S}^H_{nm}\end{pmatrix}=\frac{\rho_E}{3\rho_W}\frac{2n+1}{1+k_n'}\begin{pmatrix}\overline{C}_{nm}\\ \overline{S}_{nm}\end{pmatrix} \tag{4}$$

where ρ_E and ρ_W are mean densities of the Earth and water, respectively. Identically, a filter should be applied. The filtered water height represents physically the smoothed and spatially averaged water storage. For a filter with radius of 300 km, this means that the value is spatially weighted globally, in which the weight decreases from 1.0 to 0.5 when angular distance increases from 0 km to 300 km and quickly converges to zero when angular distance becomes larger. It is such a large area that the filtered result may not properly represent the local water storage.

As we know, the ground-based gravity change is measured at a point on the Earth's surface. However, the ground-based gravity change alone can't be used to invert the local water storage. It will be shown that combining ground-based gravity change with the space-based gravity change will be helpful to estimating local water storage. According to the descriptions in Appendix A and Eq. (4), we have

$$\Delta g^G=-2\pi G\sigma+\frac{GM}{R^2}\sum_{n=0}^{\infty}\left(\frac{-\frac{1}{2}-(n+1)k_n'+2h_n'}{1+k_n'}\right)\times\sum_{m=0}^{n}\left[\overline{C}_{nm}\cos(m\lambda)+\overline{S}_{nm}\sin(m\lambda)\right]\overline{P}_{nm}(\cos\theta) \tag{5}$$

where σ represents the equivalent water surface density at a point just below the instrument. Actually, the water just below the instrument is not isolated but collected with the surrounding water body. Hence the density at this point can represent the surrounding, i.e., local, water storage in a sense. Consequently, σ reflects the local water storage. The gravity change in the left hand side of Eq. (5) can be observed accurately by superconducting gravimeter while the second term in the right hand side can be derived from GRACE results. We can call the second term of right hand side of Eq. (5) global correction term, because it is the term to be corrected to obtain the local gravity change from ground-based gravimetry. It is noted that the effect of vertical displacement on gravity change is considered by the h'_n term between the parentheses. As a result, the water surface density σ can be obtained by combining ground- and space-based gravimetric data. Dividing σ by water density, i.e. 1.0×10^3 kg/m^3, we can obtain the equivalent local water height.

3. Application

3.1. Data and processing

For the ground-based gravimetry, we used the data measured by the superconducting gravimeter at Wuhan national geodetic observatory from June 2008 to June 2012. This station, participated in GGP (Global Geodynamics Project, Crossley et al., 1999), is located at the top of Yanjia Mountain in the suburb of Wuhan. The mountain consists mainly of the Dyas silicalite rocks with thin inter layers of shale, which are the perfect bedrock for observatory because of their great hardness and stability and powerful resistance to weathering.

During the processing, the tides were removed by a theoretical model including both Earth's tides and ocean tide loading, computed by tidal factors obtained from harmonic analysis on the SG data (Wenzel, 1996). The atmospheric effect was removed by simultaneously observed air pressure data according to the atmosphere-gravity admittance. And the polar motion effect was removed, according to Wahr's theory (Wahr, 1985), by using Earth's rotation data (http://www.iers.org). The non-tidal ocean loading is neglected, which is relatively much smaller than the hydrological effect because Wuhan SG station is far away from the ocean. Therefore, the final monthly residual dominantly contains the hydrological signal.

For the space-based gravimetry, we used *RL*05 data released by GFZ (Dahle et al., 2012) and CSR (Bettadpur, 2007) and applied the 300 km fan filter (Zhang et al., 2009). The gravity change at Wuhan station of global part was computed according to Eq. (5).

Finally the local water storage change was obtained by subtracting GRACE derived gravity change of global part from the SG derived gravity change.

Additionally, for the purpose of validation on the estimation of local water storage from gravimetry, the records of a well water table which is several meters away from the SG station were used. For comparison, the 10-min interval data were averaged to monthly ones. Furthermore, the monthly hydrological models of NOAH-GLDAS (Rodell et al., 2004) and CPC (Fan and van den Dool, 2004) were used. These two models have spatial resolutions of 0.25° × 0.25° and 0.5° × 0.5°, respectively. The water heights at Wuhan station were extracted from the