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THE INFLUENCE OF CONTINENTAL WATER STORAGE ON GRAVITY RATES ESTIMATES: CASE STUDY USING ABSOLUTE GRAVITY MEASUREMENTS FROM AREA OF LOWER SILESIA, POLAND

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ABSTRACT
In order to utilize the absolute gravity (AG) measurements in terms of tectonic study it is necessary to reduce all disturbing environmental and instrumental effects. Many of those can be easily modelled and this step is done routinely during measurements *(i.e.* tide, polar motion, ocean tidal loading). Other remains in data and there is a lack of conventional models for them. Significant gravity variation is associated with changes of soil water at global scale. We study this effect for the Lower Silesia (South-western Poland) territory. Computed gravity changes can reach up to 2 μgal peak-to-peak amplitude with seasonal time scale. This effect is beyond of accuracy of modern ballistic gravimeter. Using real data collected with FG5 gravimeter we show here that neglecting of this phenomenon can lead to serious misinterpretation in term of secular gravity changes. This is emphasized especially when only sparse data of a few year time span is at our disposal. No attempt of modelling of local hydrology impact on effect was made, while in this study we concentrate on large scale water storage influence on measured gravity.

KEYWORDS: absolute gravity, FG5 instrument, hydrology loading, Lower Silesia

1. INTRODUCTION

Absolute gravimeters (AG) reached unprecedented precision. This feature makes AG the very important tool in geophysical and geodynamics studies. In order to fully utilize the power of AG one need to take into account an impact of environmental effects on gravity measurements.

Standard AG data treatment usually takes into account such phenomena like earth tides, ocean tidal loading and polar motion. In addition the influence of atmospheric mass variation is usually modelled with single admittance factor approach (Warburton and Goodkind, 1997).

Currently, there is no any recommended conventional model which can be used for correcting AG measurements for impact of variable continental water storage. We present here the calculation of this effect using the output of global hydrology model. We draw the characteristic of the so called hydrology loading for Lower Silesia area, Southern-west part of Poland.

The importance of this phenomenon emerged in last decade and valuable papers related to this topic were already published. To name just a few we can refer to van Dam et al. (2001), Longuevergne et al. (2009), Van Camp (2010, 2011). An overall good agreement between modelled and observed gravity changes was found both in absolute and superconducting gravimeters measurement. The site dependent discrepancies stemmed from other, usually local hydrology effects. Some authors used the same WGHM hydrology model (Wziontek et al., 2009; Pálinkáš et al., 2010) and their results for amplitudes and phases for hydrology loading is consistent with these given here.

The special attention in this paper was given to impact of neglecting this effect on estimated gravity rates from repeated gravity measurements. Not sufficiently long time span of measurements can lead to erroneous gravity rates estimates. Thus misinterpretation of results in terms of geophysics (mainly tectonic) studies can occur. A few examples were given on the basis of the selected AG measurement collected with FG5 no. 230 gravimeter from the considered area.

2. GRAVITY MEASUREMENTS

We show here the examples of AG measurements taken at Lower Silesia, south west of Poland, area during the 2007-2009 period (Walo, 2010). Figure 1 show the location of gravity sites. The measurements were taken with the FG5 no. 230 absolute gravimeter in 24-hour observation sessions. The details concerning site construction and surrounding area can be found in Walo (2010).

The standard corrections for Earth tides (using tidal potential catalogue of Tamura, 1987 and model tidal parameters of Dehant et al., 1999), ocean tidal

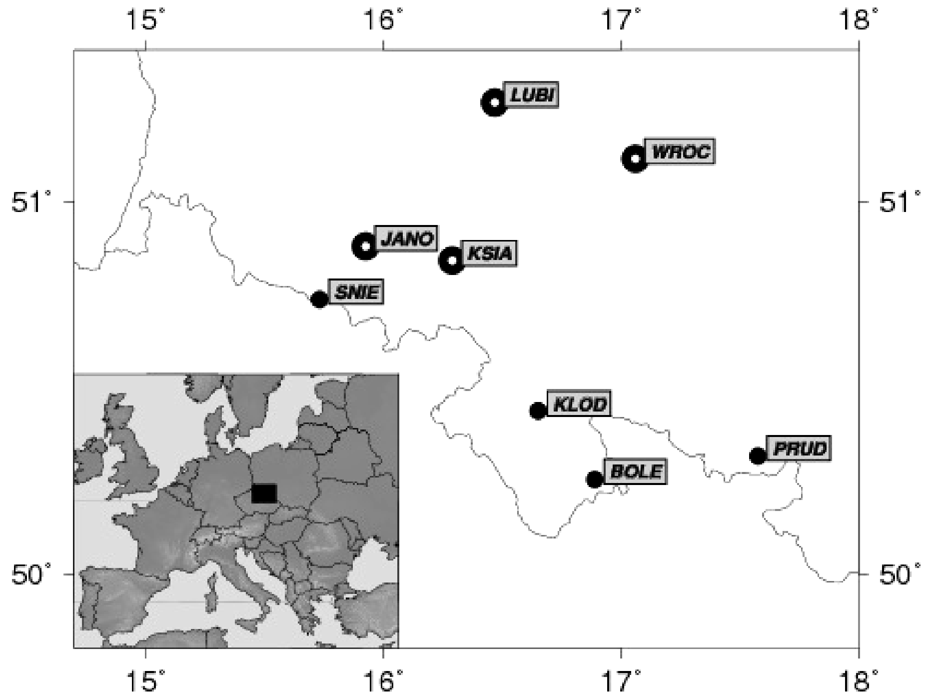


Fig. 1 Location of absolute gravity measurements. Sites where at least two measurements were performed are marked with open circles.

loading (OTL, using FES2004 model, Le Provost et al., 2004) and polar motion (Petit and Luzum, 2010) were used. For this phenomena the conventional models exist and their accuracy do not limit the feasibility of AG (Van Camp, 2003). Due to long distance to nearest ocean the OTL corrections are below the 2μGal (0.7 μGal for main M_2 constituent), and what is more important the differences in the different ocean tides models are not crucial for considered territory (Rajner, 2010). The atmospheric correction was performed using single admittance factor ($-3\text{nm}\cdot\text{s}^{-2}\cdot\text{hPa}^{-1}$) along with the barometric records (Warburton and Goodkind, 1977). This kind of atmospheric correction is appropriate in most cases. However the differences up to 2-3 μGal (during extreme weather condition) were reported when more complex approach was used (Neumeyer et al., 2004). We do not discuss here the three dimensional atmospheric gravity corrections keeping in mind that our treatment of atmospheric correction could be yet another source of error in the results (Neumeyer et al., 2004). The details of AG data processing scheme can be found in Walo (2010). In the processing of AG measurement no correction due to hydrology effects is applied. Therefore this phenomenon is one of the most significant source of error. The importance of this correction is treated in next section. It should be pointed out that in this paper we do not discuss any local hydrology effects which can be extremely important in case of gravity measurements. The values up to 10 μGal were reported (Longuevergne et al., 2009, Creutzfeldt, 2010).

The important remark at the end of this section has to be drawn. While Niebauer et al. (1995) estimated internal instrument precision slightly above 1 μGal for FG5 type gravimeter, the real accuracy (actually not known) is usually three times larger due to incomplete modelling of environmental effects (atmosphere, hydrosphere) and reduction (from instrument reference point to geodetic marker). Pálinkáš et al. (2010) made definite distinction of AG repeatability and uncertainty giving a value of 2.5 μGal for the latter. Timmen et al. (2011) using intercomparison results stated that mean absolute accuracy for thein FG5-220 gravimeter is about 3 μGal. Van Camp et al. (2011) on the basis of statistical modelling and huge amount of AG measurements concluded that gravity rates can be obtained with precision less than 1 μGal after at least 10 years of repeated (once or twice a year) measurements.

3. COMPUTATION OF HYDROLOGY LOADING

The problem of continental water storage of gravity measurement emerged in last decade when the accuracy of gravimeters and accessibility of environmental data allowed to model this effect (van Dam et al., 2001). Presently we are able to observe this effect with superconducting (Pálinkáš et al., 2010) and absolute gravimeters (Rajner et al., 2011). The impact of continental water storage on gravity was modelled using WorldGAP Hydrology Model (WGHM) output (Döll et al., 2003; Hunger and Döll, 2007). This conceptual model gives the sum of all

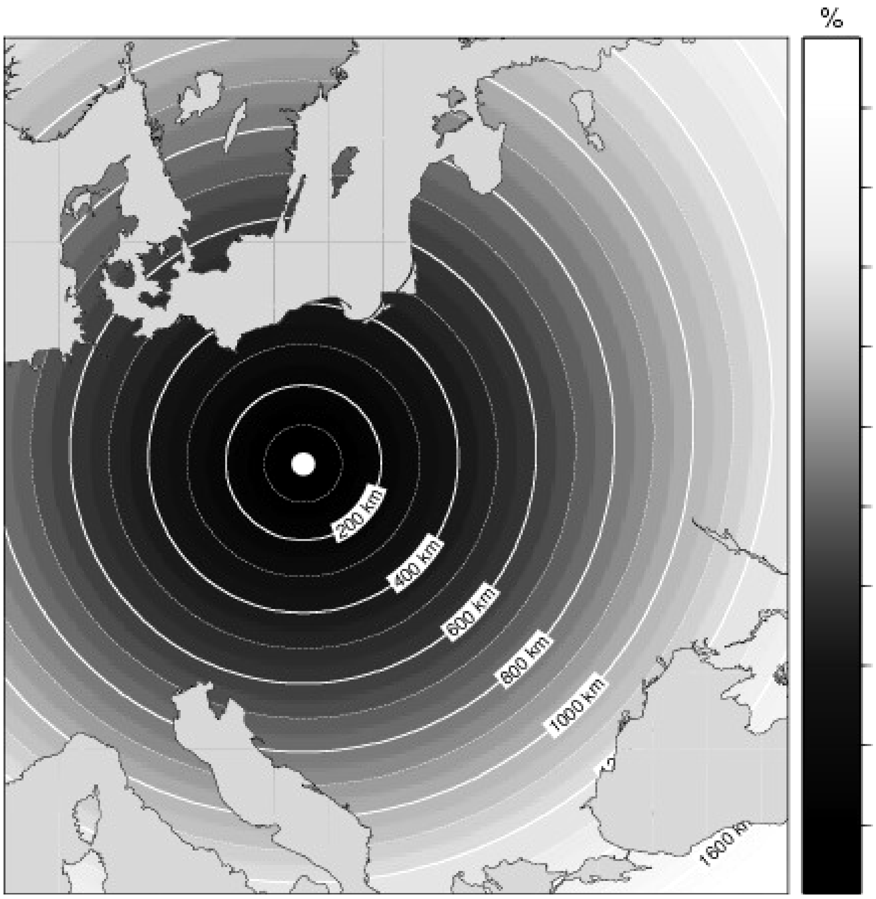


Fig. 3 The importance of calculated range of gravity changes due to continental water storage with respect to distance from Wrocław site selected for computation. The percentage value are related to range computed when the whole Earth is considered.

kind of water in hydrosphere *i.e.* canopy, snow, soil-water, groundwater, surface water (rivers, lakes, wetlands, inundation areas). The version used here has global coverage with spatial resolution of 0.5 degree (for both latitude and longitude) in monthly interval. The information of water mass distribution given in WGHM in terms of water thickness equivalent (H) along with fresh water density (ρ) was convolved with appropriate integrated Green's function (G). This can be rewritten after Farrell (1972),

$$L(r) = \rho \cdot \iint_{Earth} G(|r - r'|) \cdot H(r') dA \quad (1)$$

The dA is elementary surface area. Integrated Green's function given by Farrell (1972) was computed for PREM Earth Model (Dziewoński and Anderson, 1981). The choice of modern models is not important in loading effect computation (Bos and Baker, 2005). The functions used here reflect the sum of gravity changes connected with direct *Newtonian* attraction of water masses and indirect effect of station height changes due to loading. The loading is dominant when the global hydrology loading and site above soil is considered. Therefore we refer to hydrology loading here as the sum of both components.

The analytic expression in Equation 1 was replaced by numerical integration for computing purpose. The modified version of SPOTL software package was used here (Agnew, 1997). The code for OTL was utilised to fit our needs in order to compute the hydrological loading.

Figure 2 gives an impression of range of the hydrology loading impact on gravity. These ranges are connected with the continental water storage presented in snapshot for March and September of 2007. For Europe the changes in continental water storage are climate driven with maximum in early spring and minimum in late summer. (The time series for gravity changes are presented later in Figure 5.)

In order to underline that we are interested in continental hydrology effects we present the importance of area considered in Equation 1. Figure 3 shows the range of hydrology loading effects (computed for year 2007) which depends on area taken for computation (angular distance on sphere from selected site) relative to value obtained when the contribution from the whole Earth was considered.

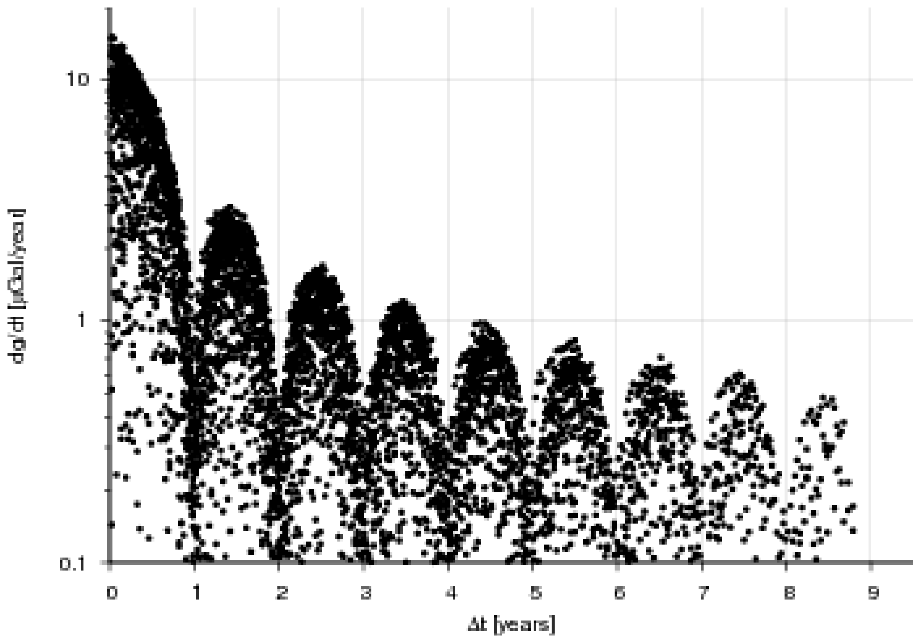


Fig. 4 The gravity rates estimation in Wrocław from ten years of global hydrology effects time series (all possible combination relative to time span were taken).

This simple demonstration confirms the necessity for the global range numerical integration in Equation 1.

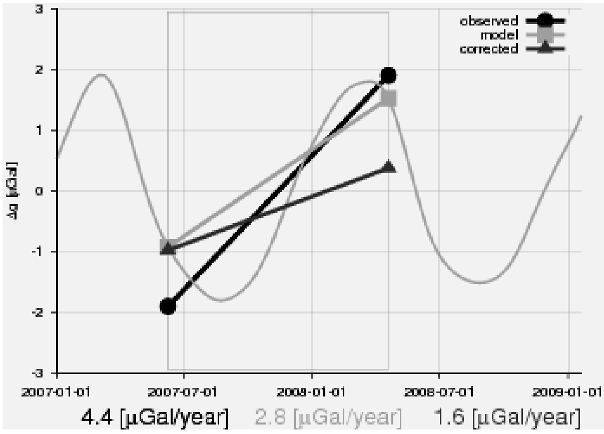
One important remark has to be given here, that we only consider the large scale continental water storage impact on gravity rates (loading and *Newtonian* part) from WGHM model. Unfortunately we do not have sufficient information to model local hydrology effects which can be crucial in terms of appropriate gravity measurements interpretation. The local hydrology effect can reach as much as ten or more µGal (Creutzfeldt et al., 2010). Pálinkáš et al. (2012) in their recent paper discussed the importance of neglecting this effect on gravity rates for central Europe. They proposed a simple method to figure out if the impact of local hydrology can amplify the predicted global hydrology effect for sites above ground level on the basis of huge data set of absolute gravity measurements. The result was ambiguous. We have to state here that local hydrology effect can change the AG results presented results significantly. Nevertheless the main goal of this study is evaluation of large scale hydrology on gravity.

4. GRAVITY RATES

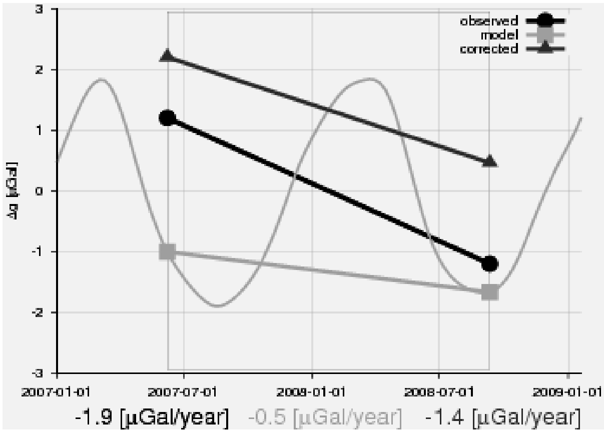
Neglecting an impact of global hydrology effects can lead to misinterpretation when one is looking for gravity rates. We used here the computed time series of hydrology loading for Wrocław (Figure 5) from the last decade. The monthly values were used to make the all possible combination of gravity difference with respect to time span. The results are presented in Figure 4. The conclusions can be drawn. Increasing time span between the measurements epochs lead to decrease of importance of the hydrology effect. On the other hand we see a great advantage of taking measurements in the same season within consecutive years. At least 4-5 years of observations are necessary if the error from global hydrology loading below 1 µGal is necessary.

5. CORRECTING GRAVITY MEASUREMENTS

The real data was used to present the impact of hydrology effects on gravity rates. In Figure 5 we show the gravity rates estimated from AG measurements. On the same Figure we put the modelled impact of continental water storage variation time series and gravity rates for this effect between the epochs when measurements were taken. The corrected gravity rates were simply computed subtracting global hydrology correction from measurements in relevant epochs. The graphs show that the trends of gravity changes can be seriously changed when considered effect is neglected. The global hydrology correction (or all environmental effects in general) seems to be especially important in tectonically inactive sites where gravity rates are very small, like for these presented here. The presentation of gravity rates from two measurements only and with only a few years time span is inappropriate, especially if we keep in mind the nominal accuracy of AG. Thus Figure 5 presents graphical conviction of global hydrology importance. The other clarification is that we chose two sites where correction seems to be proper while for the other two our approach has no meaning for



(a) Wrocław



(b) Janowice Wielkie

Fig. 5 The time series of global hydrology effects on gravity, the measured gravity (centred values) and corrected gravity values for selected sites. The computed gravity rates are printed respectively.

gravity rates. Probably this is due the presence of other dominant source of errors or geophysical phenomena (Kaczorowski, 2011, personal communication). For the Lubiąż site (Fig. 1) the problem may stem from dominant local hydrology and the fact that pillar is located beneath the ground level. The other possible explanation is neglecting of local hydrology which is out of the scope of this work, but it is strongly site dependent.

The recent work of Pálinkáš et al. (2012) supports our findings and statements that hydrological effect is crucial in terms of interpreting gravity variation. Their conclusions are in accordance with those presented here and are even more reliable while they used much more gravity measurements. Moreover these were taken in the central Europe close to Lower Silesia thus continental water storage variation influence on gravity was of the same range.

6. CONCLUSIONS

Neglecting global hydrology effects can lead to misinterpretation when one is looking for gravity rates (Van Camp et al., 2010). Within this work we showed that modelled gravity changes due to continental water storage can reach as much as a 3-4 μGals of peak-to-peak amplitude on the Lower Silesia area (central Europe). Keeping in mind accuracy of AG we demonstrated that this subtle effect can be crucial when gravity rates from sparse measurements needs to be defined. We presented the results for two selected AG sites where neglecting hydrology loading leads to serious misinterpretations in terms of tectonic or geodynamic studies. The seasonal regularity of considered phenomenon allows to mitigate impact on gravity rates estimation when measurements are taken with the same season within different years (this also concerns other environmental effects like long term atmosphere loading). One should be aware that we did not consider local hydrology effects in this study as we concentrated our study on large scale continental water storage loading and because of lack of sufficient in-situ auxiliary measuerements.

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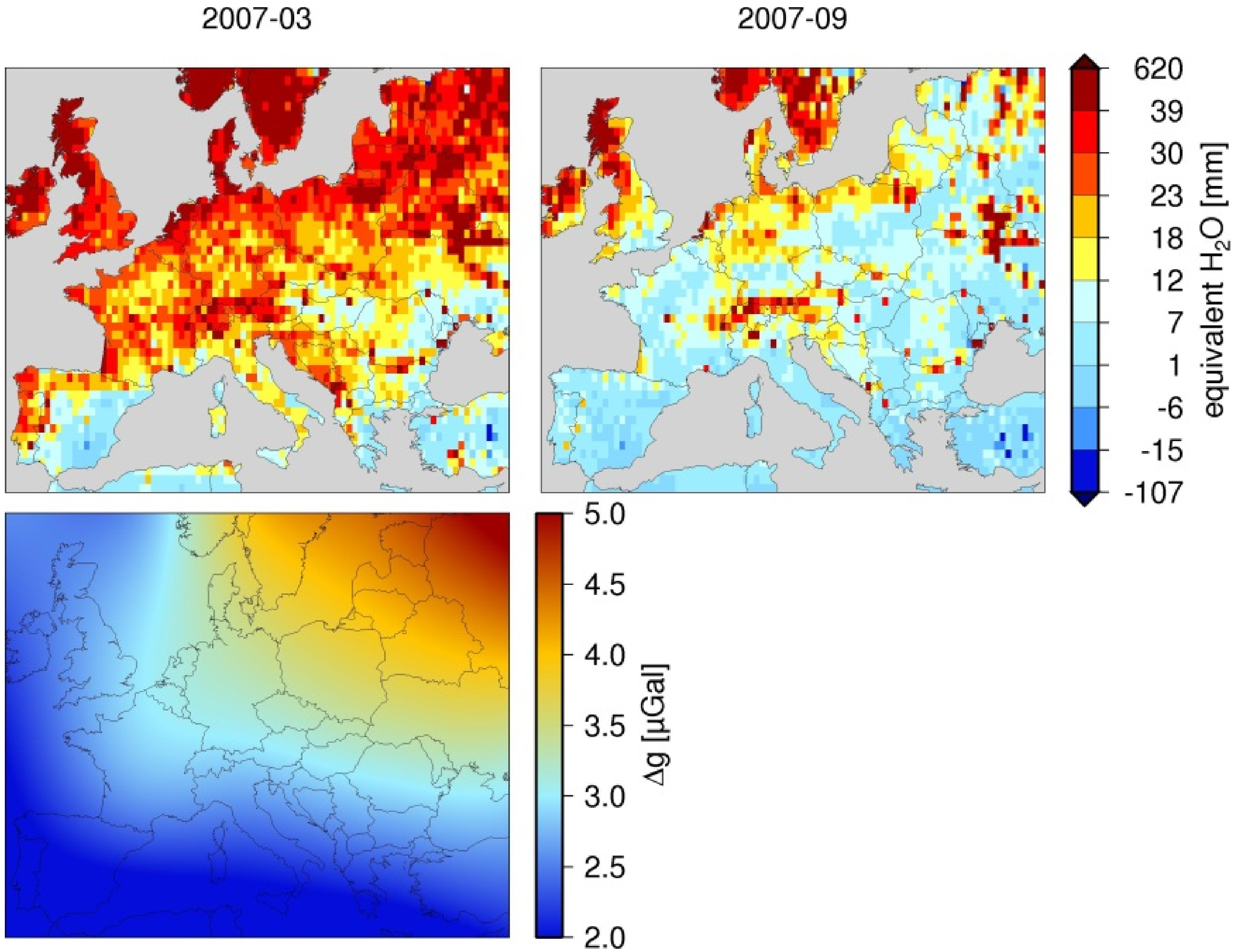

Fig. 2 Amplitude of seasonal gravity changes due to hydrological loading in Europe in 2007 (bottom map) connected with seasonal variation of continental water storage presented in upper graph. (Two snapshots for March and October from WGHM output in terms of water layer thickness. This shows the extreme variation of water amount within the year. The negative value for water equivalent reflects the model design.)