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Reducing local hydrology from high-precision gravity measurements: a lysimeter-based approach

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GJI Gravity, geodesy and tides

SUMMARY

Temporal gravimeter observations, used in geodesy and geophysics to study the Earth's gravity field variations, are influenced by local water storage changes (WSC). At the Geodetic Observatory Wettzell (Germany), WSC in the snow pack, top soil, unsaturated saprolite and fractured aquifer are all important terms of the local water budget. In this study, lysimeter measurements are used for the first time to estimate the hydrological influence on temporal gravimeter observations. Lysimeter data are used to estimate WSC at the field scale in combination with complementary observations and a hydrological 1-D model. From these estimated WSC, we calculate the hydrological gravity response. The results are compared to other methods used in the past to correct temporal gravity observations for the local hydrological influence. Lysimeter measurements significantly improve the independent estimation of WSC and thus provide a better way of reducing the local hydrological effect from gravimeter measurements. We find that the gravity residuals are caused to a larger extent by local WSC than previously stated. At sites where temporal gravity observations are used to study geophysical processes beyond local hydrology, the installation of a lysimeter is recommended.

Key words: Time variable gravity; Hydrogeophysics; Hydrology; Europe.

INTRODUCTION

Ground-based temporal gravity observations are gaining importance in a wide range of geophysical research issues. Gravimeter observations have been used to study long-term geodynamic processes such as post-glacial rebound (e.g. Lambert *et al.* 2006; Sato *et al.* 2006; Steffen *et al.* 2009), processes in the Earth's mantle and core (e.g. Imanishi *et al.* 2004; Shiomi 2008), natural hazards like, for example, gravity changes associated with earthquakes and volcanism (e.g. Battaglia *et al.* 2008; Nawa *et al.* 2009), reservoir-monitoring applications like, for example, hydrocarbon and geothermal exploration and carbon sequestration (e.g. Brady *et al.* 2008; Sugihara & Ishido 2008) and the comparison of ground-based with satellite gravity measurements like, for example, comparison with GRACE (e.g. Neumeyer *et al.* 2008; Weise *et al.* 2009). To study relative gravity variations in time, superconducting gravimeters (SG) (Goodkind 1999) are currently the best performing gravimeters in terms of precision and temporal resolution. Advances in atom interferometry promise the time-continuous application of absolute gravity measurements in the future (Peters *et al.* 2001; de Angelis *et al.* 2009).

Ground-based temporal gravimetric observations are influenced by up to tens of μGal by natural local water storage changes (WSC) like changes in groundwater, soil moisture, snow or surface water storage (Bonatz 1967; Lambert & Beaumont 1977; Mäkinen & Tattari 1988; Bower & Courtier 1998; Crossley & Xu 1998; Hasan *et al.* 2008; Pool 2008). WSC affect temporal gravity measurements on the event and seasonal timescale but can also show long-term changes due to natural and human-induced trends (e.g. Rodell *et al.* 2009). The hydrological effect is an intrinsic feature of ground-based temporal gravity measurements and can mask the geodetic/geophysical phenomena of interest. Therefore, it has to be removed from the gravimeter signal for geodetic/geophysical studies.

To correct for the hydrological influence in gravity measurements, the change of water masses has to be estimated around the gravimeter and from these mass variations the hydrological gravity effect has to be calculated. The estimation of temporal variations of spatially distributed water storages and the calculation of the hydrological gravity response is a data intensive and challenging task. Different approaches have been developed to correct for the hydrological influence in gravity measurements. We can distinguish between empirical approaches, which establish a statistical relationship between hydrological and gravity data (Lambert & Beaumont 1977; Harnisch & Harnisch 2002; Imanishi *et al.* 2006) and physically based approaches, which calculate the gravity response from WSC based on the Newtonian law (Virtanen 2001; Hokkanen *et al.* 2006; Kroner *et al.* 2007; Meurers *et al.* 2007). Some approaches use mainly observation data to directly measure WSC (Van Camp *et al.* 2006; Longuevergne *et al.* 2009) whereas other approaches rely on hydrological models to estimate the local WSC. Different hydrological models have been applied in the context of local gravimeter measurements, ranging from simple, lumped and conceptual models (Jacob *et al.* 2008; Lampitelli & Francis 2010) to more complex, distributed and physically based models (Hasan *et al.* 2008; Kazama & Okubo 2009; Naujoks *et al.* 2009). Hydrological models are driven by measured precipitation and climate data, but data about the system (pedophysical properties, soil moisture, groundwater, etc.) or the system output (discharge) are fundamental to parameterize/calibrate the hydrological model. Often, detailed data about the hydrological system and the geometric settings are not available so that the gravity signal is used to calibrate the approach/model. Hence, we can also distinguish between approaches that estimate the effect of local WSC independently from gravity measurements (Creutzfeldt *et al.* 2010a) and approaches that calibrate the model to match the gravity signal (Hasan *et al.* 2008; Lampitelli & Francis 2010). Finally, the large-scale hydrological gravity effect on gravimeter observations (Llubes *et al.* 2004; Neumeyer *et al.* 2008; Wziontek *et al.* 2009b) is considered before (Jacob *et al.* 2008; Longuevergne *et al.* 2009) or after focusing on local WSC (Hasan *et al.* 2008; Weise *et al.* 2009). No standard procedure for reducing the hydrological effect has been introduced up to now as suggested by Harnisch & Harnisch (2006). For studies using temporal gravity observations to investigate geophysical phenomena beyond local hydrology, a standardized approach is needed to independently estimate local WSC and remove the hydrological gravity response from gravimeter measurements. However, estimating local WSC from independent observations or models is associated with a high level of uncertainty, making signal reduction a challenging task (Creutzfeldt *et al.* 2010a).

In hydrology, weighable lysimeters provide us with an accurate measurement of the soil moisture change by continuously recording the mass of a soil monolith. Lysimeters can be considered very accurate devices to measure precipitation and deep drainage and they are, in fact, the only device to directly measure the actual evapotranspiration (Yang *et al.* 2000; Meissner *et al.* 2007; WMO 2008; Tolk & Evett 2009). The Geodetic Observatory Wettzell (Schlüter *et al.* 2007) is the only place where both gravimetric monitoring systems—a state-of-the-art lysimeter and a dual sphere SG—operate in parallel at a distance of around 40 m. The aim of this study is to use the lysimeter as an independent monitoring device to correct temporal high-precision land-based gravity measurements for the influence of local WSC without performing any calibration against the gravimeter residuals. We will compare this lysimeter-based approach to other methods, that is, a statistics-, model- and data-based approach, which exemplarily stand for approaches reported in literature for correcting the gravity signal for hydrological influence.

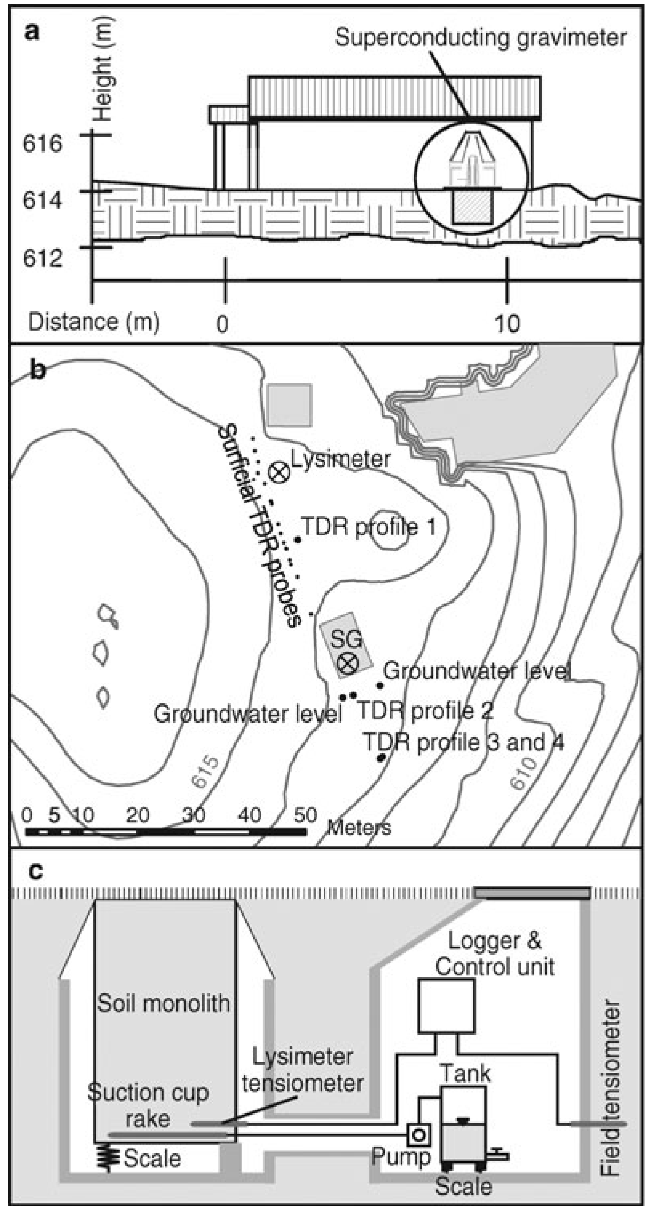

Figure 1. (a) Cross-section of the SG building of the Geodetic Observatory Wettzell, (b) location of the lysimeter, the SG and the different hydrological sensors in combination with a contour map, and (c) cross-section of the lysimeter [modified according to von Unold & Fank (2008)].

DATA AND METHOD

Data

Temporal gravity variations were observed with the GWR SG CD029 at the Geodetic Observatory Wettzell (Fig. 1). Apart from an instrumental drift, SGs are high-precision instruments with a noise level of 5 $[(\text{nm s}^{-2})^2]\,\text{Hz}^{-1}$. This corresponds, for example, to a level of 0.02 μGal during a period of 100 s (Banka & Crossley 1999; Van Camp *et al.* 2005). After the elimination of spikes, disturbances, and offsets during pre-processing, the SG data were combined with absolute gravity measurements to determine scale factor and instrumental drift (Wziontek *et al.* 2009a). Then, the gravity effects of known non-hydrological effects, that is, solid earth tides, ocean tide loading and polar motion (Hinderer *et al.* 2007) as well as mass changes in the atmosphere (Klügel & Wziontek 2009) were modelled and removed from the SG data. The remaining signal is hereinafter referred to as 'SG residuals'.

At the Geodetic Observatory Wettzell, a hydrological monitoring system was installed to observe the water in different storages and hydrological fluxes (Creutzfeldt *et al.* 2010a, b). Precipitation was measured by two heated tipping bucket rain gauges. Evapotranspiration was estimated based on air temperature, relative humidity, wind speed, and global radiation data. Snow height and snow water equivalent was measured with an ultrasonic height sensor and a snow pillow. Soil moisture sensors based on the Time Domain Reflectometry (TDR) technique measure the top soil moisture (0.0–0.3 m).

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Soil moisture up to a depth of 2.0 m was monitored with TDR sensors installed in four different soil profiles. Next to the SG building, the groundwater level was recorded in two boreholes (Fig. 1).

In 2007 July, a UMS lysimeter with a 1.5 m deep undisturbed soil monolith and a surface area of 1 m^2 was installed to measure the mass change in snow and soil water. Comparable water regimes and drainage conditions in the lysimeter and in the field (e.g. no capillary barrier) were achieved by suction control of the lower lysimeter boundary. At the lower boundary, a tensiometer in the lysimeter and another one in the corresponding depth in the field measure the soil matric potential. The matric potential measured in the field was applied via a suction cup rake and a bidirectional pump to the lower boundary of the lysimeter by pumping water into a drainage water tank or into the monolith. The monolith and the drainage water tank were placed on a high-precision scale for continuous mass recording (Fig. 1). The reader is referred to the study of von Unold & Fank (2008) for a detailed description.

Precipitation, actual evapotranspiration and deep drainage were estimated from the lysimeter monolith and the drainage water weight, assuming that during a sample interval (1 min) either evapotranspiration or precipitation occurs. Precipitation, actual evapotranspiration and deep drainage can be estimated with an accuracy of 0.01 mm as stated by the manufacturer, but the accuracy is reduced due to wind effects on the weight measurements. Nonetheless, lysimeters measure precipitation more precisely than common precipitation gauges because lysimeter measurements are not affected by the wind field effects and wetting losses of precipitation gauges (Richter 1995; Allerup 1997).

The snow water equivalent estimated by the snow pillow was subtracted from the lysimeter weight to distinguish between mass changes in the snow and soil storage since mass changes in the snow storage have a different gravity effect than mass changes in the soil (Creutzfeldt *et al.* 2008). For the study period from 2008 July 30 to 2009 July 30, all data were processed to 1 hr intervals. The mean was calculated for parameters being measured several times (groundwater level, soil moisture in the same depth).

Lysimeter-based approach

Fig. 2 shows the study design of the lysimeter-based approach to estimate the total local WSC defined as

$$\mathrm{WSC}_{\mathrm{local}} = \Delta S_{\mathrm{Snow}} + \Delta S_{\mathrm{Soil}} + \Delta S_{\mathrm{Saprolite}} + \Delta S_{\mathrm{GW}} \quad (1)$$

for the Geodetic Observatory Wettzell. WSC in the snow and soil storage ($\Delta S_{\mathrm{Snow}} + \Delta S_{\mathrm{Soil}}$) depend on the precipitation (P), the actual evapotranspiration (ETa) and the deep drainage (D)

$$\Delta S_{\mathrm{Snow}} + \Delta S_{\mathrm{Soil}} = P - \mathrm{ETa} - D. \quad (2)$$

The water balance equation for the saprolite and groundwater storage ($\Delta S_{\mathrm{Saprolite}} + \Delta S_{\mathrm{GW}}$) is expressed in its general term as

$$\Delta S_{\mathrm{Saprolite}} + \Delta S_{\mathrm{GW}} = D - Q, \quad (3)$$

where D is the deep drainage and Q the groundwater discharge. Up to a depth of 1.5 m, the lysimeter directly measured $\Delta S_{\mathrm{Snow}} + \Delta S_{\mathrm{Soil}}$. $\Delta S_{\mathrm{Saprolite}} + \Delta S_{\mathrm{GW}}$ was estimated based on the lysimeter deep drainage (here equal to D) and groundwater level measurements. The vertical water redistribution below the lysimeter and the groundwater discharge (Q) were estimated with the hydrological model HYDRUS 1Dů (Šimůnek *et al.* 2008). Water flow in the subsurface was described by the van Genuchten–Mualem soil hydraulic model (Mualem 1976; van Genuchten 1980) with the following parameters: residual water content (θ_r), saturated water content (θ_s),

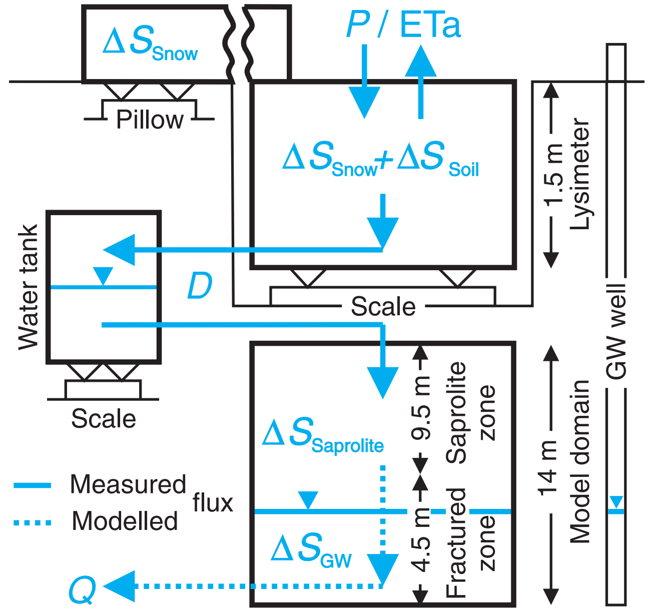

Figure 2. Hydrological study design. Snow water change (ΔS_{Snow}) is measured by a snow monitoring system. Snow and soil water change ($\Delta S_{\mathrm{Snow}}+\Delta S_{\mathrm{Soil}}$) by the lysimeter up to a depth of 1.5 m. A hydrological model is used to estimate the WSC in the saprolite and groundwater ($\Delta S_{\mathrm{Saprolite}}+\Delta S_{\mathrm{GW}}$) up to a depth of 15.5 m. Precipitation (P), actual evapotranspiration (ETa), and drainage (D) are directly measured fluxes (solid lines). Percolation and groundwater discharge (Q) are modelled (dotted line).

Table 1. Subsurface hydraulic parameters: residual water content (θ_r), the saturated water content (θ_s), inverse of the air entry pressure (α), pore size distribution index (n), pore connectivity (l), and saturated hydraulic conductivity (K_s) (Creutzfeldt *et al.* 2010a).

		Unit	Saprolite	Fractured bedrock
Depth	From	m	1.5	11
	To		11	19
θ_r		$m^3\ m^{-3}$	0	0
θ_s		$m^3\ m^{-3}$	0.38	0.02
α		cm^{-1}	2.64	2.64
n		–	1.23	1.23
l		–	0.5	0.5
K_s		$m\ h^{-1}$	0.002	0.0108

inverse of the air entry pressure (α), pore size distribution index (n), pore connectivity (l), and saturated hydraulic conductivity (K_s) (Table 1). In this study, we use the parameter set estimated in Creutzfeldt *et al.* (2010a) from field and laboratory measurements. The depth below the lysimeter was divided into the saprolite (1.5–11.0 m) and the fractured bedrock zone (11.0–19.0 m). For the saprolite zone, the soil hydraulic parameters (θ_r, θ_s, α, n) were estimated from water retention measurements of undisturbed soil samples and K_s from laboratory and field measurements. The same parameter values for θ_r, α, and n were applied for the fractured zone because taking and analysing undisturbed soil samples for the fractured zone is challenging (Katsura *et al.* 2005). We assume that fractures are filled with the same material as the saprolite zone. Based on these parameters and the specific yield (S_y) of the aquifer estimated from a pump test, the parameter θ_s was derived assuming that the specific yield represents the water content between saturation and field capacity. From the pump test, the conductivity K_s was estimated for the fractured zone. For both zones, the parameter l is set to be 0.5 (Mualem 1976). In line with a gradual transition from saprolite to bedrock, the contrast of K_s and θ_s between both zones was smoothed by linear interpolation between a depth of 8.0 and 11.0 m.

The upper boundary flux of the hydrological model was defined by the deep drainage measured with the lysimeter. The lower boundary was defined by the mean of both groundwater levels as a variable head condition. The initial moisture profile was estimated during a warm-up period starting on 2007 July 18. For this period, no lysimeter measurements were available for the upper boundary conditions. Therefore, deep drainage was derived from tensiometers based on the Buckingham–Darcy approach (Creutzfeldt *et al.* 2010a).

The gravity response of estimated WSC was calculated from the hydrological observations and model results with a spatially nested extended point mass approach (MacMillan 1958; Leirião *et al.* 2009) presented by Creutzfeldt *et al*. (2008) for an area of 4 × 4 km^2 around the SG in Wettzell and taking into account the spatial distribution of WSC along and below the topography. The gravity response of snow, soil water, the saprolite, and groundwater storage change was calculated in relation to the beginning of the study period as the reference date. The distribution of WSC in the near field has a major influence on the estimated gravity response (Creutzfeldt *et al.* 2008). The effect of the SG building, and foundation was considered assuming that (1) snow accumulates on the roof of the SG building, (2) no WSC occur in the foundation of the SG and the base plate of the SG building, and (3) the SG building prevents infiltration of water into the ground from above (umbrella effect) but lateral fluxes may occur to some extent in the subsurface. As an approximation for the last assumption, we calculated the average gravity response for cases excluding and including mass variations below the base plate.

Other approaches for comparison

Following the different correction methods presented in the Introduction, we set up the statistics-based approach, which is an empirical approach. Considering the importance of various WSC components at Wettzell, we included groundwater, soil moisture in different soil depths, and snow data in the analysis. A backward stepwise regression suggested that all parameters have a statistically significant predictive capability for the SG residuals, so all data were included in the multiple linear regression model. Table 2 shows the parameters and statistics for the multiple linear regression model, which was used to predict the hydrological gravity response from hydrological data.

The model-based approach uses the conceptual hydrological model of Creutzfeldt *et al.* (2010b). The model estimates WSC using the following input data: (1) mean precipitation measured by the two gauges, (2) the reference evapotranspiration for short canopy derived from climate data, and (3) snow height. The gravity response from WSC was calculated with the extended point-mass approach based on a spatially nested discretization domain (Creutzfeldt *et al.* 2008). Instead of using the assumption made on the WSC distribution below the SG building, we introduced parameters that could vary between the two cases: mass variations were excluded and included below the base plate. These parameters as well as the hydrological model parameters were calibrated based on the Generalized Likelihood Uncertainty Estimation (GLUE) method (Beven & Binley 1992), but for simplicity, only the mean of the behavioural model runs is used for further processing. In this context, this is a physically based approach, but the hydrological model parameters and the WSC distribution in the near field were calibrated against the SG residuals. The model was calibrated for a different time period (2005 July 1 to 2008 July 30) than the study period.

A third approach, the data-based approach similar to the study of Creutzfeldt *et al.* (2010a), uses snow observations, TDR soil moisture measurements, and groundwater levels data to calculate the gravity effect based on the approach presented in the previous section. This is an independent and physically based approach. The estimated specific yield from a pump-test of 1 per cent is used to derive the mass changes for the aquifer. In general, it is difficult to install sensors to measure WSC in the vadose zone below a depth of ∼2 m. Hence, WSC in this zone are generally neglected. Following this and due to a lack of observations for this study period, we will not consider WSC estimated by Creutzfeldt *et al.* (2010a) for the saprolite zone, knowing that we underestimate the hydrological gravity effect. Additionally, we modified this data-based approach by simply subtracting the soil moisture gravity response from the SG residuals and then estimating the specific yield by linear regression between the remaining SG signal and groundwater level. This modified approach is a mixed form of the statistics- and data-based approach.

Large-scale hydrological gravity effect

The large-scale hydrological gravity effect (Llubes *et al.* 2004; Neumeyer *et al.* 2008) was derived based on the approach presented by Wziontek *et al.* (2009b) using WSC simulated by

Table 2. Parameters, statistics and performance criteria of the multiple linear regression model for the statistics-based approach to predict the SG residuals from hydrological measurements.

Variable	Regression coefficient	Standard error	t-value	p-value
Intercept	5.71	0.27	21.09	<0.001
Groundwater	−2.02	0.01	−189.00	<0.001
Soil moisture				
2.0 m	20.06	1.00	20.09	<0.001
1.5 m	25.67	1.24	20.66	<0.001
1.0 m	53.03	2.18	24.36	<0.001
0.6 m	−82.51	2.76	−29.88	<0.001
0.4 m	73.40	2.03	36.22	<0.001
0.3 – 0.0 m	−4.97	0.34	−14.43	<0.001
Snow	58.77	0.65	89.83	<0.001

Estimate of standard deviation of error: 0.61452 — Multiple R^2: 0.952
F-statistic 21 610 on 8 and 8751 degrees of freedom — p-value: 0

global hydrological models. To account for uncertainties of global hydrological models, we used the WaterGAP Global Hydrology Model (WGHM, Döll *et al*. 2003) and four different land surface models (CLM, MOSAIC, NOAH and VIC) of the Global Land Data Assimilation System (GLDAS) (Rodell 2004). For each model, we calculated the large-scale gravity effect of Newtonian attraction and the effect of deformation due to the changing load on the Earth's surface. The attraction effect of a near zone of less than 50 km around the SG in Wettzell was excluded.

RESULTS AND DISCUSSION

Lysimeter-based approach

In the study period, cumulative precipitation measured by the lysimeter was 1140 mm (Fig. 3a). The actual evapotranspiration was measured to be 541 mm and deep drainage to be 591 mm. Except for precipitation, all time-series show distinct seasonal variations. Actual evapotranspiration decreases to nearly zero in the winter and strongly increases with the start of the vegetation period. Water storage measured by the lysimeter (sum of soil and snow storage) starts to increase in autumn to reach a maximum at the end of February. No deep drainage is observed during winter time (2009 January–February) because soil freezing prevents soil water movement and causes an accumulation of water in the lysimeter system (Fig. 3a). Snowmelt in February/March causes a strong decrease of the lysimeter weight and an increase of the deep drainage followed by a groundwater rise of ∼2.2 m (Fig. 3b).

The time-series of the SG residuals and the gravity response to WSC agree well in amplitude, phase and short-term variations (Fig. 3c). A shift between both time-series exists caused by an extreme rainfall event of 64 mm per 2 hr on 2008 July 31, which may have lead to a disturbance of the system during its spin-up period. The overall seasonal amplitudes for the SG residuals and the gravity response amount to 9.5 and 8.8 μGal, respectively. For

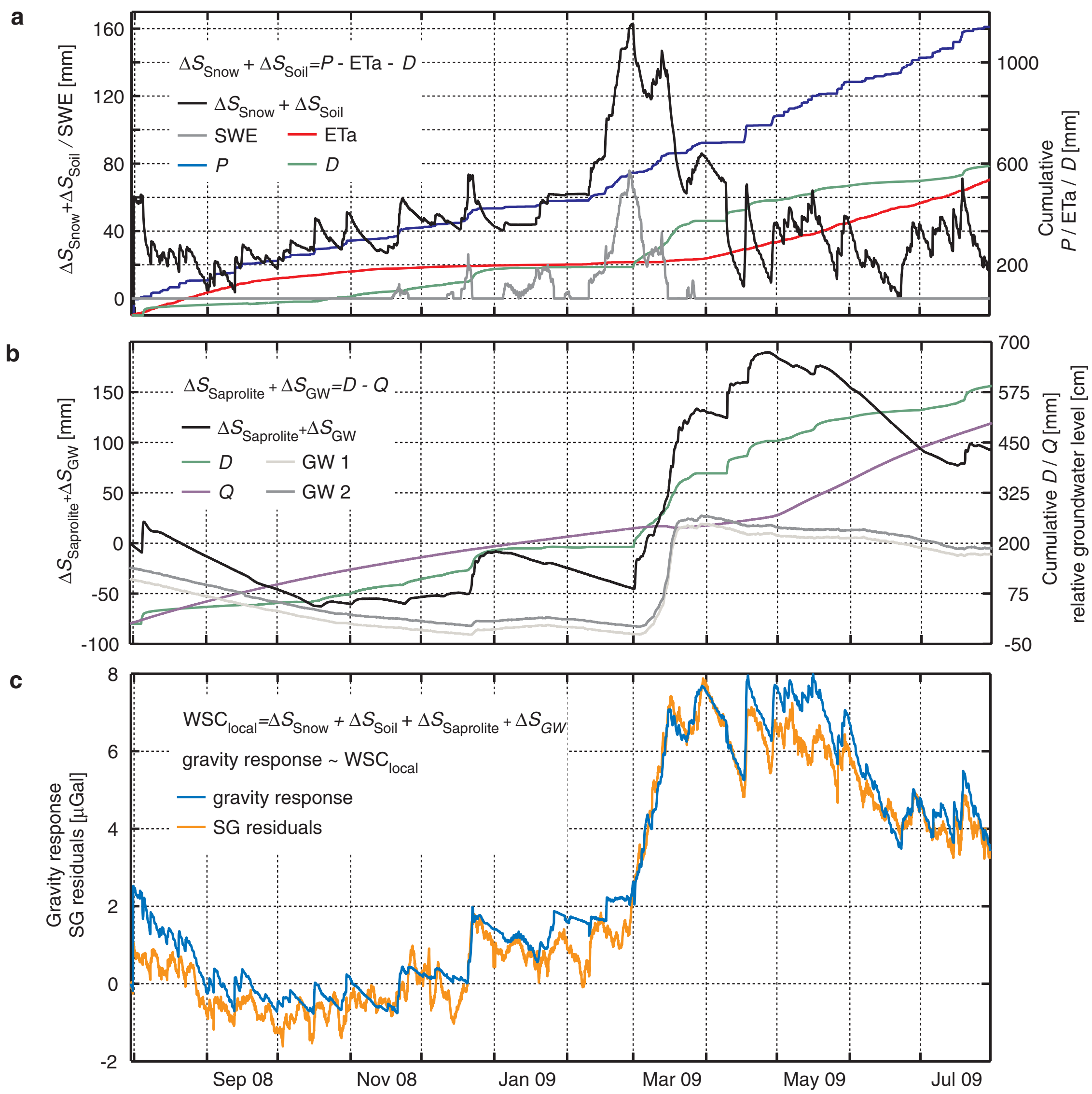

Figure 3. (a) Time-series of lysimeter weight change ($\Delta S_{Snow}+\Delta S_{Soil}$), snow water equivalent (SWE), cumulative precipitation (P), cumulative evapotranspiration (ETa), and cumulative drainage (D). (b) Time-series of water storage changes in the saprolite and groundwater ($\Delta S_{Saprolite}+\Delta S_{GW}$), cumulative drainage from lysimeter (D), cumulative groundwater discharge (Q), relative groundwater levels [GW 1 & GW 2; absolute groundwater table depth = 1400 – relative groundwater level (cm)]. (c) Time-series of the SG residuals and the total hydrological gravity response derived with the lysimeter approach.

the lysimeter-based approach, the regression slope of 0.98 and a corresponding coefficient of determination of 0.97 reflect a good agreement in phase and magnitude of the SG residuals and the lysimeter-based approach (Table 3). Short-term variations in SG residuals are strongly influenced by rainfall and snowmelt events and related snow and soil moisture changes. The seasonal variations are mainly associated to WSC in the saprolite and aquifer zone. A wetting front travelling through the hydrological system causes an exponential decline of the WSC. Translated into gravity response, the recession curves tend to become linear and thus agree with the linear character of the SG residuals (Fig. 3c).

Comparison to other approaches

Hydrological gravity responses estimated with the different approaches are compared in Fig. 4. The statistics-based approach explains 95 per cent of the variance of the SG signal. However, the model parameters cannot be interpreted in a physical way. Due to the correlation of soil moisture measurements at different depths, soil moisture data can substitute each other in a regression analysis so that the regression coefficient can become negative (e.g. soil moisture at a depth of 0.6 m in Table 2). The correspondence between the model-based approach and SG residuals (97 per cent of explained signal variation) is also very high, but it is problematic to interpret the internal model structure or individual parameter sets of these conceptual models in a physical way (Creutzfeldt *et al.* 2010b). The data-based approach agrees well with the SG residuals in terms of short-term variations, but when a specific yield of 1 per cent as derived from a pump test (Creutzfeldt *et al.* 2010a) is used, the seasonal variation of the SG residuals is underestimated. The specific yield was estimated to be 7 per cent by linear regression between groundwater data and the soil moisture reduced SG signal. Using this value, the estimated gravity signal explains 89 per cent of the SG residuals. However, a specific yield of 7 per cent is unrealistically high given the pump test results. Significant deviations between data-based estimated gravity response and SG residuals can be identified during the winter (2009 January–March). The estimated decrease of gravity response is caused by the apparent decrease of soil moisture in the top soil (Fig. 4a: soil moisture 0.0–0.3 m) caused by the change of the dielectric permittivity due to soil freezing. This serves to show that it is difficult to use electromagnetic (EM) methods to estimate surface soil moisture during winter time when ground frost occurs. For the statistics-based approach, the apparent decrease of soil moisture in the top soil zone is compensated by a small regression coefficient for the top soil zone (Table 2).

The correlation of gravimetric time-series and local WSC found in this study is higher than previously estimated for Wettzell before lysimeter data were available or for other gravity sites with less extensive hydrological observations. For Wettzell, the variability of the SG residuals explained by independently estimated WSC ranged between 37 and 77 per cent and the RMSE varied between 1.57 and 5.70 μGal (Creutzfeldt *et al.* 2010a). Longuevergne *et al.* (2009) estimated the local hydrological gravity effect deterministically and explained 31 per cent (RMSE 1.55 μGal) of SG residual variations for the Strasbourg observatory (personal communication, 2010). The approach developed by Van Camp *et al.* (2006) to estimate the local hydrological gravity effect explained 53 per cent (RMSE 1.02 μGal) of SG residual variations for the geodynamic station in Membach (time-series extended to 2009; personal communication, 2010). For the SG at the Geodynamic Observatory Moxa, variations of the SG residuals explained by local WSC that had been fitted against the SG residuals ranged between 77 (Krause *et al.* 2009) and 80 per cent (Hasan *et al.* 2008), whereas Naujoks *et al.* (2009) showed that seasonal variations of the SG residuals of Moxa become visible only after reducing the signal for the local hydrological gravity effect. In the study of Lampitelli & Francis (2010), a conceptual model was calibrated against SG residuals, which explained 77 per cent of the variation of the SG residuals at the Walferdange Underground Laboratory for Geodynamics.

One explanation for the higher correspondence is that lysimeters are considered to be an accurate method to quantify near-surface hydrological flux and storage variations. A higher representativeness is given due to a sampling volume of the lysimeter that is larger by a factor of 1500 compared to EM soil moisture sensors (with an assumed sampling volume of 1000 cm^3). EM sensors in access tubes have often been used in previous studies, but the accuracy, variability, and physical significance of these EM sensors as field soil moisture measurements have been called into question (Mazahrih *et al.* 2008; Evett *et al.* 2009). The present approach combining the lysimeter measurements with a well-constrained physically-based model and complementary data for deeper zones suggests that the derived WSC are currently as close to reality as we can get in terms of estimating total WSC at the field scale. Nonetheless, the estimated hydrological gravity response is associated with uncertainties arising from hydrological measurement accuracy, assumptions and simplifications in the structural model of the subsurface, hydro(geo)logical parameter estimation, spatial variability of WSC, distribution of WSC in the near field (e.g. below the SG building), and processing of the SG residuals. They were not evaluated in this study. In this uncertainty chain, the distribution of WSC in the near field is considered to have the largest influence on the results.

Another explanation for the higher correlation between the estimated gravity response and SG residuals is that WSC occur almost exclusively below the level of the gravity-sensing unit at the Wettzell station (except for snow). This implies that vertical gravity effects are unidirectional only. At SG sites where water mass variations can occur below and above the sensor, their effects might partially cancel each other out and hydrological flow processes, that is, vertical

Table 3. Statistical comparison of SG residuals and the different approaches to estimate the hydrological gravity response and the standard deviation of the reduced SG residuals.

Approach	RMSE	Coefficient of correlation	Coefficient of determination	Slope (SG versus approach)	Standard deviation
Lysimeter-based	0.615	0.987	0.975	0.982	0.44
Statistics-based	0.614	0.976	0.952	0.952	0.61
Model-based	0.473	0.986	0.973	1.01	0.47
Data-based ($S_y = 1.0$ per cent)	2.079	0.816	0.666	0.333	1.98
Data-based ($S_y = 7.0$ per cent)	1.556	0.891	0.793	1.079	1.56

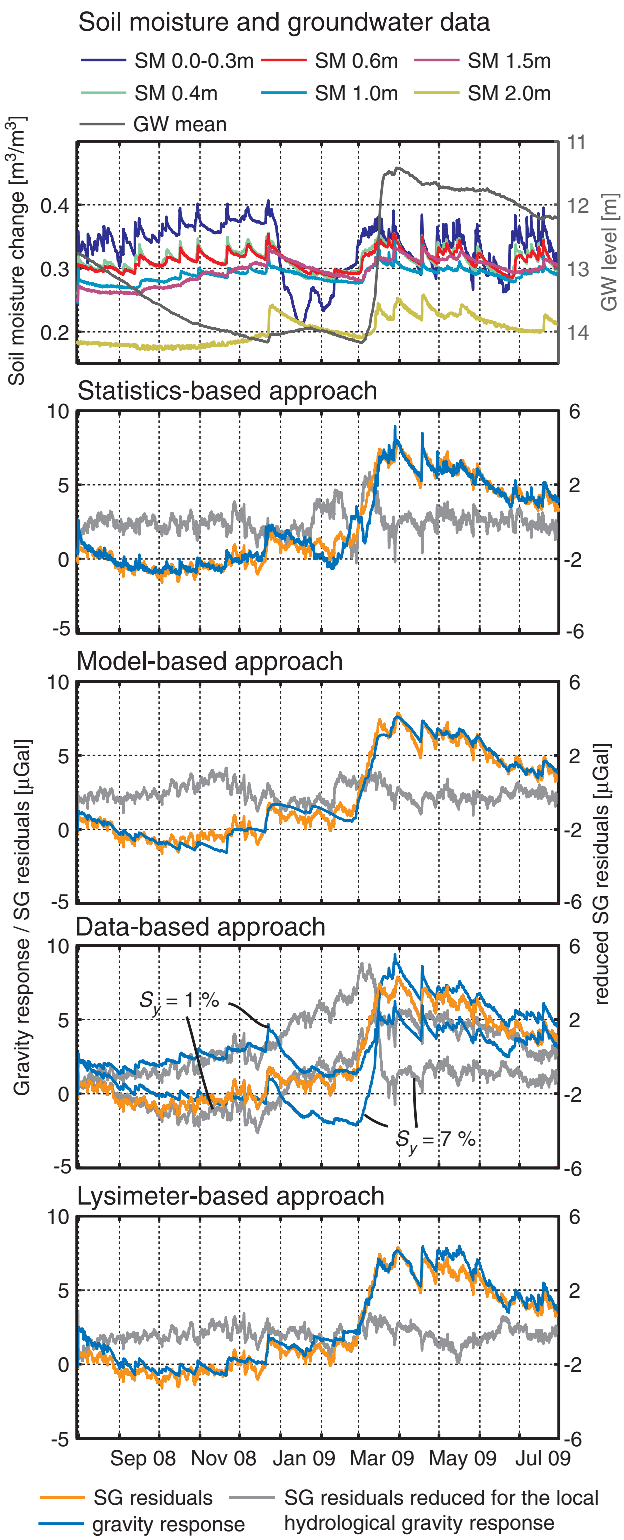

Figure 4. Soil moisture (SM) observed in different depths and groundwater data. Gravity response estimated based on the different approaches. SG residuals and the differences between both time-series (reduced SG residuals) for each approach.

processes leading to water mass redistribution from above (negative gravity effect) to below (positive gravity effect) the gravimeter are very important. This makes the SG signal interpretation more complicated because hydrological flow processes have to be quantified.

Comparison to the large-scale hydrological gravity effect

Fig. 5 shows the SG residuals reduced for the local hydrological gravity response (hereinafter referred to as 'reduced SG residuals') in comparison to the modelled large-scale hydrological gravity effect. The reduced SG residuals may reveal other geophysical gravity effects as discussed in the Introduction. For the Geodetic Observatory Wettzell, it can be assumed that reduced SG residuals will mainly be caused by large-scale hydrological mass variations because, for a start, all other geophysical signals can be considered to be very small at this station. Using the data-based approach for the local hydrological reduction, the reduced SG residuals show seasonal variations and are significantly correlated (p value < 0.05) to the large-scale hydrological gravity effect of the hydrological models WGHM, GLDAS CLM, and GLDAS NOAH, but not GLDAS MOSAIC and GLDAS VIC (Table 4). The data-based approach with a specific yield of 7 per cent is correlated only to the global hydrological models because the apparent decline of soil moisture due to soil freezing adds a 'seasonal' component to the reduced SG residuals.

The statistics- or model-based approaches explain nearly all of the SG residuals, and therefore, the reduced SG residuals are not significantly correlated to the large-scale hydrological effect. The higher correlation coefficient for the statistics-based approach is again due to soil freezing. The overall poor correlation is not surprising because both approaches were calibrated to best fit the SG data. This finding generally calls into question the benefits of these types of local hydrological reduction when the goal is to study other geophysical processes based on the reduced SG residuals. The calibration to the SG data may accidentally remove part (or all) of the signal of interest, in particular if the reduction method is flexible enough to be adjusted to complex SG residual time-series. This is the case in this study, where both the multilinear regression and the conceptual hydrological model have enough parameters, that is, degrees of freedom, to be efficiently adjusted to the SG signal.

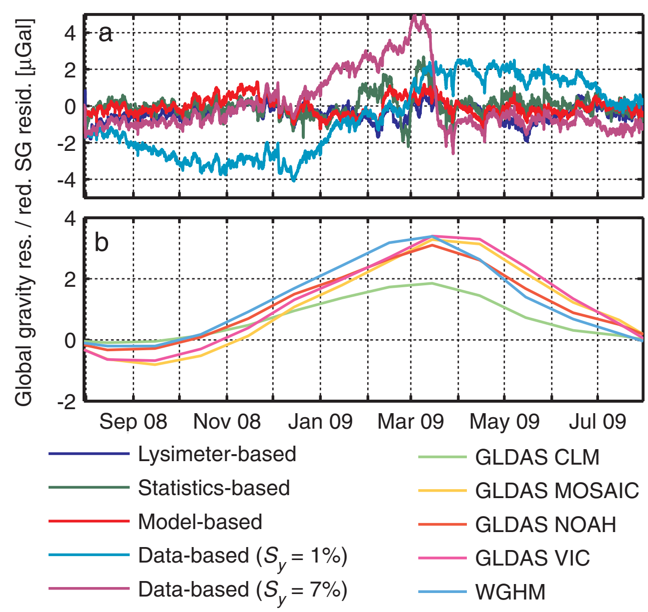

Figure 5. (a) SG residuals reduced for the local hydrological gravity response using different approaches in comparison to (b) the large-scale hydrological gravity effect estimated using the different hydrological models.

Table 4. Correlation coefficient and the corresponding *p*-value (in brackets) of the SG residuals reduced for the local hydrological gravity response and the large-scale hydrological gravity effect.

	WGHM	GLDAS CLM	GLDAS MOSAIC	GLDAS NOAH	GLDAS VIC
Lysimeter-based	0.26 (0.41)	0.27 (0.42)	0.14 (0.66)	0.20 (0.53)	0.13 (0.68)
Statistics-based	0.54 (0.07)	0.54 (0.07)	0.45 (0.14)	0.50 (0.10)	0.44 (0.15)
Model-based	0.14 (0.66)	0.13 (0.69)	−0.04 (0.91)	0.06 (0.85)	−0.03 (0.92)
Data-based ($S_y = 1.0$ per cent)	0.50 (0.10)	0.47 (0.12)	0.75 (<0.00)	0.60 (0.04)	0.72 (0.01)
Data-based ($S = 7.0$ per cent)	0.75 (0.04)	0.76 (<0.00)	0.51 (0.09)	0.65 (0.02)	0.51 (0.09)

No significant correlation exists between the reduced SG residuals of the lysimeter-based approach and the modelled large-scale hydrological gravity effect (Table 4). The standard deviation of the reduced SG residuals is small with less than 0.5 μGal, which is even smaller than for the calibrated approaches. This is surprising because the lysimeter-based reduction was derived completely independently from the SG data. Two possible explanations exist as to why both signals are not correlated. They are discussed in the following taking into account that the study period extends only over 1 yr.

On the one hand, one may argue that the missing correlation is due to errors/uncertainties in estimating the local hydrological gravity effect. In particular, if the local hydrological gravity effect was overestimated and correlated to the global effect, its removal may have accidentally left no global signal in the residuals. The local hydrological gravity effect might be overestimated due to uncertainties in estimating the WSC distribution in the near field. In particular, it could not be determined to which extent the observed WSC in the natural environment around the SG building apply to the zone below the base plate of the building. Errors resulting from this ‘blind zone’ are considered to be the most important source of uncertainty, but uncertainties arising from hydrological measurement accuracy, assumptions and simplifications in the structural model of the subsurface, hydro(geo)logical parameter estimation, spatial variability of WSC, calculation of the gravity response, and processing of the SG residuals may also influence the result. However, an observed trend of about 4 μGal in the SG residuals for the study period could be explained by the local WSC but was not existent in the modelled large-scale hydrological gravity effect. In addition, the large-scale hydrological gravity effect can be considered a relatively smooth signal because it is a cumulative signal of many small-scale hydrological events. It is not likely that these small-scale events occur at the same time. Hence, the short-term variations of the SG residuals cannot be caused by large-scale hydrological variations, rather local WSC can explain most of these variations (Fig. 3). This provides some evidence that possibly the local hydrological gravity effect is not overestimated by the lysimeter-based approach.

On the other hand, a correlation between the reduced SG residuals and the large-scale hydrological gravity effect might not be observed due to high uncertainties in the quantification of the large-scale hydrological gravity effect associated with the estimation of large-scale WSC. For example, we estimated the seasonal amplitude of the large-scale hydrological effect for the GLDAS CLM to be 2 μGal and for GLDAS NOAH to be 4 μGal (Fig. 5b). This is in line with the statement of Neumeyer *et al.* (2008) that the uncertainties from models in estimating the global hydrological effect are in the same range as the signal itself. Additionally, we calculated the Newtonian attraction and deformation effect from WSC as suggested by different other studies, accounting for the continental part of water storage only (Llubes *et al.* 2004; Jacob *et al.* 2008; Weise *et al.* 2009; Wziontek *et al.* 2009b). This approach, however, neglects a fundamental exchange process of the global water cycle, that is, namely, water redistribution between the continents and the oceans and related water mass changes of the global ocean. Neglecting global water mass conservation may result in an overestimation of the Newtonian attraction term while the deformation effect should not be significantly affected because it is considered to be a regional phenomenon (Wziontek *et al.* 2009b). The influence of water mass conservation on the large-scale hydrological gravity effect will be subject of further investigations. Furthermore, the evaluation of the deformation term should be accomplished in Wettzell by other geodetic measurement systems, namely Global Navigation Satellite Systems (GNSS), Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR) measurements.

However, the existing uncertainties question the possible approach of subtracting the large-scale hydrological gravity effect from SG residuals before focusing on the local hydrological signals. In summary, a remaining key question in using SG measurements for the investigation of the large-scale hydrological gravity effect is the ‘scaling problem’ caused by uncertainties due to WSC distribution in the near field of a few metres around the SG. The impact of constructions, soil sealing, and drainage will make the very near water storage and transport dynamics considerably different from the local water regime under more natural conditions in larger distances around the building and, hence, has to be more carefully addressed to enhance the value of SG data.

Conclusions

In this study, lysimeter measurements are used for the first time to estimate the hydrological influence on temporal gravimeter observations. Lysimeter measurements in combination with a well-constrained 1-D hydrological model and additional observation data (soil hydraulic and groundwater data) are used to estimate total local WSC and the corresponding hydrological gravity effect for the Geodetic Observatory Wettzell.

The results of the lysimeter-based approach were evaluated in comparison to a statistics-, model-, and data-based approach, which represent methods used in previous studies to correct for the local hydrological gravity effect. Approaches calibrated against the SG residuals (statistics- and model-based approach) can explain 95–97 per cent of the variation of the SG residuals, but it is very difficult to interpret the fitted model as well as the remaining unexplained part of the SG residuals. Any additional non-hydrological gravity signal of interest may have partly been removed due to the fitting procedure. Thus, the benefit of these approaches for geophysics and geodesy can be questioned.

Therefore, it is necessary to estimate the local hydrological gravity effect independently from the gravimeter measurements. The data-based approach shows the limitations of using only snow, groundwater, and near-surface soil moisture data to estimate the total WSC at the field scale. High uncertainties associated with the estimation of hydrological fluxes and specific yield may above all hinder the estimation of WSC in deeper subsurface zones. WSC in the groundwater and in particular in the unsaturated saprolite zone are especially important components of the seasonal and long-term water storage budget. Short-term variations in the SG residuals can largely be explained by snow mass and near-surface soil moisture changes related to precipitation and snowmelt events. When trying to estimate these changes, uncertainties arise from technical problems of EM sensors like, for instance, the failure of EM sensors during ground frost. Lysimeters, in contrast, allow for the direct and precise estimation of precipitation, evapotranspiration, deep drainage, and soil moisture change and for an indirect estimation of WSC in the deep vadose and aquifer zone. Furthermore, lysimeters can also measure WSC during periods of frost and snowmelt provided that the effect of snow bridges is considered.

At sites where temporal gravity observations are undertaken, the installation of a state-of-the-art lysimeter (weighable, suction-controlled and monolith-filled) is recommended in case the gravity signal should be corrected for local WSC. The installation of a lysimeter seems to be justified in view of the very high cost of high-precision temporal gravity observations (lysimeters cost less than ∼one-tenth of an SG). The lysimeter should be combined with a site-specific hydrological observation strategy to monitor total WSC at the field scale.

The gravity response of the lysimeter-based estimated total WSC is in very good agreement with the SG residuals and the gravity residuals are caused to a larger extent by local WSC than previously stated. This highlights the importance of considering the effect of local WSC in all storage components of ground-based temporal gravity observations on the event and seasonal timescales but long-term WSC might also exist. Hence, extreme caution should be applied when interpreting gravity residuals in terms of large-scale hydrological variation. Gravity variations of geophysical origin can be masked by local hydrological mass transfer processes, but a lysimeter-based approach can accurately estimate the WSC to correct the temporal gravity signal for the hydrological gravity effect. This will significantly enhance the interpretation of the gravity signal to study geophysical processes with ground-based temporal gravity observations.

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