Modeling the Hydrological Effect on Local Gravity at Moxa, Germany

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ABSTRACT

A superconducting gravimeter has observed with high accuracy (to within a few nm s^{-2}) and high frequency (1 Hz) the temporal variations in the earth's gravity field near Moxa, Germany, since 1999. Hourly gravity residuals are obtained by time averaging and correcting for earth tides, polar motion, barometric pressure variations, and instrumental drift. These gravity residuals are significantly affected by hydrological processes (interception, infiltration, surface runoff, and subsurface redistribution) in the vicinity of the observatory. In this study time series analysis and distributed hydrological modeling techniques are applied to understand the effect of these hydrological processes on observed gravity residuals. It is shown that the short-term response of gravity residuals to medium- to high-rainfall events can be efficiently modeled by means of a linear transfer function. This transfer function exhibits an oscillatory behavior that indicates fast redistribution of stored water in the upper layers (interception store, root zone) of the catchment surrounding the instrument. The relation between groundwater storage and gravity residuals is less clear and varies according to the season. High positive correlation between groundwater and gravity exists during winter months when the freezing of the upper soil layers immobilizes water stored in the unsaturated zone of the catchment. To further explore the spatiotemporal dynamics of the relevant hydrological processes and their relation to observed gravity residuals, a GIS-based distributed hydrological model is applied for the Silberleite catchment. Driven by observed atmospheric forcings (precipitation and potential evapotranspiration), the model allows the authors to compute the variation of water storage in three different layers: the interception store, the snow cover store, and the soil moisture store. These water storage dynamics are then converted to predicted gravity variation at the location of the superconducting gravimeter and compared to observed gravity residuals. During most of the investigated period (January 2000 to January 2004) predictions are in good agreement with the observed patterns of gravity dynamics. However, during some winter months the distributed hydrological model fails to explain the observations, which supports the authors' conclusion that groundwater variability dominates the hydrological gravity signal in the winter. More hydrogeological research is needed to include groundwater dynamics in the hydrological model.

1. Introduction

Detecting change in water storage from related temporal variation in gravity has become an important issue for many studies and research related to the earth and environmental science, in particular to oceanography, climatology, hydrology, and geophysics. Finding the relation between water storage and gravity change is promising for hydrologists, in closing the water balance, as well as for geophysicists, in detecting the real long-term gravity change and improving the signal-to-noise ratio in different frequency ranges.

The Global Geodynamics Project (GGP) (Crossley et al. 1999) began in 1997 with the purpose of recording the earth's gravity field with high accuracy at a number

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of stations around the world using superconducting gravimeters. The Gravity Recovery and Climate Experiment (GRACE) (Tapley et al. 2004), jointly implemented by the National Aeronautics and Space Administration (NASA) and Deutsche Zentrum fur Luft- und Raumfarht (DLR), is a dedicated twin-satellite mission (launched in March 2002) whose objective is to map the Earth's gravity field to high accuracy at monthly intervals. Both GGP and GRACE recognize that tracking the movement of water on and beneath the Earth's surface is one of the main goals, and thus promise a significant development in hydrological studies.

Although there is a general understanding about hydrological effect (more qualitative than quantitative) on gravity, gravity did not get much attention from hydrologists until the GRACE mission was initiated. A number of studies have focused on detecting continental and monthly scale water storage change from GRACE gravity fields using both synthetic and real data (Rodell and Famiglietti 1999, 2001, 2002; Swenson and Wahr 2002; Swenson et al. 2003; Wahr et al. 2004), but only a few report on deducing catchment-scale fast-responding hydrologic processes from terrestrial gravity observations. Gravity is mostly corrected for hydrological effect by finding and applying empirical relations of different (available) hydrometeorological data (precipitation, soil moisture, groundwater) with gravity residuals (Mäkinen and Tattari 1988; Peter et al. 1995; Bower and Courtier 1998; Crossley and Xu 1998; Kroner 2001; Harnisch and Harnisch 2002), while the hydrological processes responsible for redistribution of water storage are generally ignored or strongly simplified. In this study we not only look at the available hydrometeorological observations, but also try to explain the gravity dynamics in terms of relevant hydrological processes and physical properties of the area considered.

Classical distributed catchment-scale hydrological models that have been optimized for use with sparse in situ observations are often inappropriate for exploiting remote sensing data and thus have to be extended or significantly rethought and reformulated (Troch et al. 2003). For any given catchment scale the relation between gravity variation and storage (mass) change in principle should be the same. Incorporating data on gravity variation in catchment-scale hydrological modeling can greatly enhance our understanding of flow and storage processes and may lead to improved data assimilation techniques, for instance, by constraining water balance fluctuations. Through this study we explore the possibility of incorporating gravitational change in hydrological process modeling. The main objectives of this study are therefore 1) to explore high-resolution gravity and hydrometeorological time series to detect causal relationships in a small catchment and 2) to evaluate the ability to explain gravity residuals by means of distributed hydrological modeling.

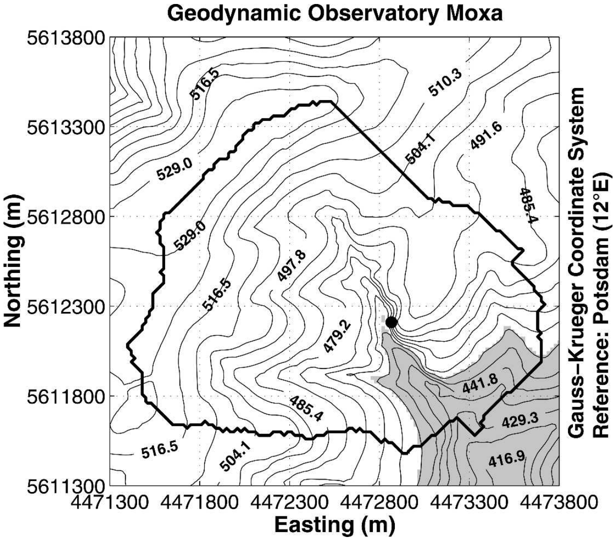

FIG. 1. Surrounding topography of the Geodynamic Observatory Moxa. Contours are in m +MSL, thick line shows the catchment boundary, the dot indicates the gravimeter location, and the shaded area is lower than the elevation of the gravimeter.

2. Data and methods

GGP consists of a network of 21 superconducting gravimeters distributed around the world, where investigation is required to detect and model hydrological effect on gravity. The data used in this study are collected at the Geodynamic Observatory Moxa in Germany (Fig. 1).

The Geodynamic Observatory Moxa is located in the Silberleite Valley at the border of Thuringian Slate Mountains of Germany. The observatory was partly built into a hill in order to reduce noise caused by industrial plants, major roads, and towns and to enhance temperature stabilization. The stability of the observation site mainly arises from the bedrock. The bedrock consists of steeply dipping layers of intensively folded and fractured shales. The elevation of the catchment varies between 375 and 535 m +MSL, with gentle and steep hillslopes. Most of the surrounding area within the catchment is above the gravimeter (Fig. 1). The Silberleite Valley at the observatory is a second Strahler order catchment with intermittent and ephemeral streams. The main runoff generation process is saturation excess in the riparian zone. The soil layer (including the weathering layer) has mostly a depth be-

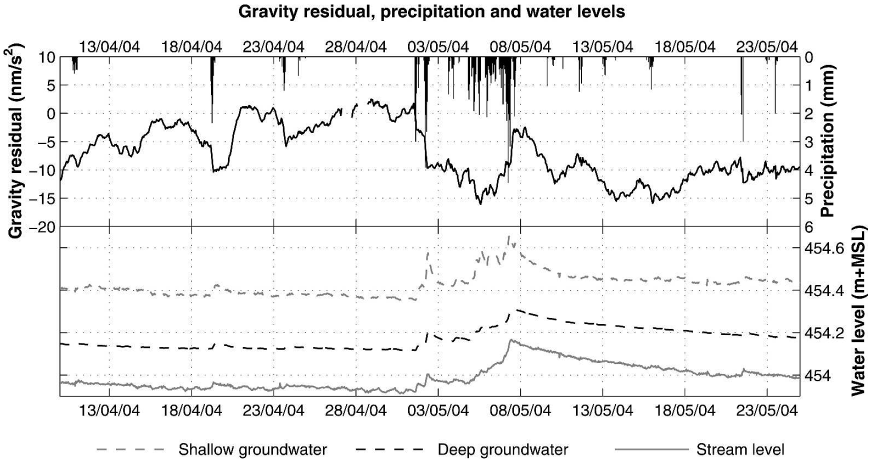

FIG. 2. Exploring gravity residuals as a function of precipitation and water levels (note that precipitation is hourly accumulation). Black solid line is for gravity residuals, upper bars are for precipitation, and lower lines are for water levels.

tween 0.5 and 1.0 m, and the vegetation cover is mainly spruce forest.

The hourly gravity residuals, hereafter referred to as observed gravity residuals, are obtained after reductions for earth tides, polar motion, barometric pressure, and instrumental drift [more information about site-specific gravity reduction can be found in Kroner et al. (2004)]. The hydrometeorological data, collected in the vicinity of the observatory, include hourly precipitation, deep groundwater (filter at 48 m below land surface), air pressure, temperature, wind speed, humidity, and illuminance and occasionally sampled surface water levels at a V-notch installed in the Silberleite. The above-mentioned data collection started during the second half of 1999. At the end of 2003, additional piezometers were installed near the observatory at a depth ranging between 1 and 2 m to monitor the shallow groundwater table, together with an automatic water-level recorder upstream of the V-notch.

To explore gravity and hydrometeorological time series to detect causal relationships in our catchment we apply different data analysis techniques on the available time series. Our primary interest is in quantifying gravity variation based on total water storage change in the vicinity of the observatory. In the available hydrometeorological time series, we have two variables that are directly related to water storage: precipitation, representing the hydrological input, and deep groundwater table, measuring the hydrological state of the catchment. As we are dealing with a small catchment (≈ 3 km^2), we consider the point precipitation to be uniformly distributed over the whole catchment. This assumption is supported by the nature of most storms in the area being generated by frontal systems with spatial scales much larger than our catchment. We apply time series modeling, namely, impulse response functions (IRF) to quantify precipitation effect on gravity for selected medium- to high-rainfall events. In contrast to precipitation in the small catchment, the groundwater table is highly variable in space. As a result, point piezometric level cannot represent the spatial distribution of saturated storage. We therefore apply time series analysis to achieve a qualitative description of the relation between deep groundwater and observed gravity residual.

To evaluate the ability to explain gravity residuals by means of distributed hydrological modeling we apply the Soil Moisture Routing (SMR) model (Boll et al. 1998) to estimate the water storage dynamics in the unsaturated zone. We then compute the gravity variation caused by water storage change in the unsaturated zone using Newton's law of gravitation in a local Cartesian coordinate system.

In the following sections we present the main findings of the data analysis and modeling to quantify gravity change due to observed and modeled hydrological processes near the observatory.

3. Exploring gravity and hydrometeorological time series

a. Precipitation and gravity

From visual inspection of the precipitation and gravity residuals (Fig. 2) it is clear that precipitation has a direct and short-term effect on gravity. Any considerable precipitation (≈ 5 mm or more) event around the observatory causes the gravity signal to drop. Figure 2 clearly demonstrates the drop caused by precipitation

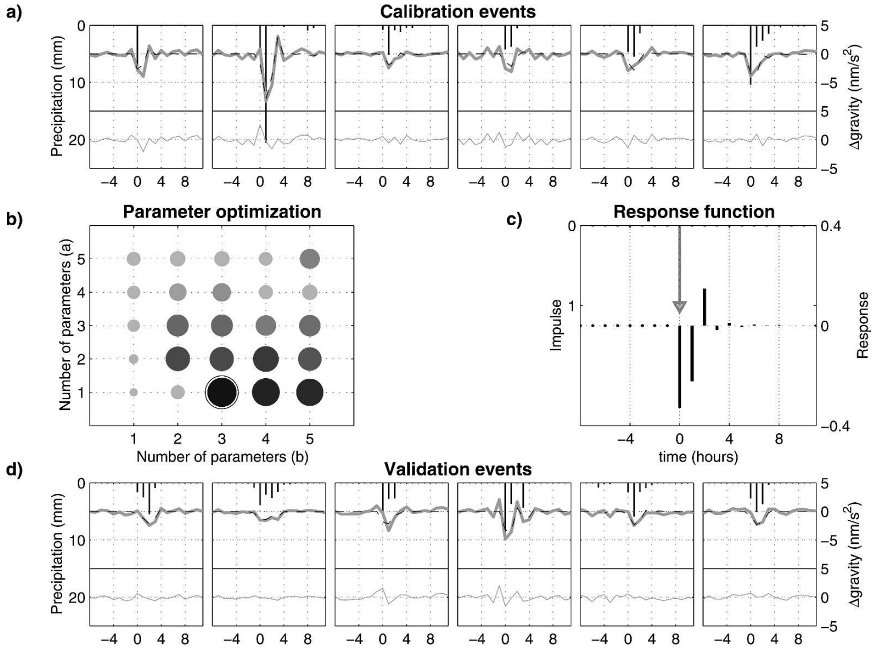

FIG. 3. Short-term gravity response to rainfall impulses. (a) Model calibration showing selected precipitation events (vertical bars) along with observed (thick gray line) and modeled (dashed line) changes in gravity residuals (top) and model error (thin gray line at bottom). (b) Model structure characterization: a and b represent number of parameters in autoregressive and moving-average polynomials of the transfer function. Size and shade of the circles represents values of −BIC. The optimized value is marked by a circle ($b = 3$, $a = 1$). (c) Optimized unit impulse (arrow showing precipitation) response (black bars showing gravity change) function. (d) Model validation showing selected precipitation events (vertical bars) along with observed (thick gray line) and modeled (dashed line) changes in gravity residuals (top) and model error (thin gray line at bottom).

event, except during the period 6–8 May 2004, when there was a continuous precipitation event. During a continuous event (for days), simultaneous redistribution of water input into the deeper layer would account for different dynamics in the gravity signal (see later). The drop, observed during short isolated events of significant amount, can be explained by the fact that most of the surrounding area is above the gravimeter (Fig. 1). Any additional mass above the gravimeter will cause the gravity signal to decrease under the condition of uniform rainfall distribution over the instrument's spatial domain. This short-term effect of precipitation on gravity can be efficiently and accurately modeled by means of linear transfer function models (Box and Jenkins 1976). We consider 4-h-long periods of considerable precipitation (>8 mm) events isolated by 8-h-long periods of dry spells (maximum precipitation <1 mm h^{-1}). The above-mentioned thresholds of dry and wet periods are selected based on the available data, and the selected events are grouped as calibration and validation events.

We compute the IRF for these selected calibration events using the z transform, which is a mathematical operation that, when applied to a sequence of numbers, produces a polynomial function of the variable z. We use a Bayesian information criterion (BIC) (Priestley 1981) that weighs model performance to complexity and allows for parsimonious model structure identification. The IRF provides insight into the short-term response of gravity due to rainfall impulses. If $u_{(k)}$ and $y_{(k)}$ denote the input (precipitation in mm during hourly time intervals) and output (gravity changes in nm s^{-2} during the same hourly time intervals), the transfer function in the z-transform domain can be represented as

$$y_{(k)} = \frac{-0.33 - 0.42z^{-1} + 0.01z^{-2} + 0.07z^{-3}}{1.00 + 0.61z^{-1}} u_{(k)}, \tag{1}$$

where z^{-1} indicates the backward shift operator, such that $z^{-1}u_{(k)} = u_{(k-1)}$ and k is a discrete time step counter.

Figure 3 shows the construction of the impulse response function, which explains 62% and 57% of the variance of observed gravity change during calibration and validation periods, respectively. The observed and modeled variances are 1.79 and 1.11 during calibration and 1.31 and 0.75 during validation. Figures 3a and 3d show some selected events along with observed and modeled gravity change during calibration and validation. The IRF demonstrates (Fig. 3c) the instantaneous drop in gravity caused by a unit precipitation input. The gravity decreases further in the next hour and partially recovers in the following hour. A possible explanation for this recovery is that it mimics the fast hydrological processes in the vicinity of the observatory. After an initial impulse of the rainfall, more or less uniformly distributed around the observatory, redistribution governed by surface and subsurface flow processes allows the gravity signal to recover partially from the immediate drop in magnitude. Our results support our assumption on uniform rainfall distribution, otherwise we would not find that the linear transfer function model would be able to explain gravity changes for different rain events in a very similar way.

Explaining the gravity residuals by means of the impulse response function is valid only for short-term gravity changes that occur because of a precipitation impulse. A precipitation event can also mean a water mass loading on the surface. The loading effect of local (area of a few square kilometers) water masses on gravity is negligible, as it is on the sub nm s^{-2} scale and not detectable by the gravimeter. The IRF does not account for redistribution or loss of water in the catchment at larger time scales (days). For long-term gravity changes we need to look at the storage changes induced by redistribution of available water in the subsurface. Our next step is exploring gravity with deep groundwater, which represents, to some extent, the available storage of the catchment at a given moment in time.

b. *Groundwater and gravity*

Unlike precipitation effects on gravity, the effect of groundwater change is less trivial. Both the deep and shallow piezometers react instantaneously to precipitation and coincide with the quick water-level changes in the stream (Fig. 2). From this observation we can conclude that both the deep and shallow aquifers are well connected to the stream that drains the area surrounding the gravimeter and excludes the possibility of a confined groundwater system. As discharge (flux) is proportional to available water storage (state), the deep or shallow groundwater store represents the water storage condition of the catchment. Although the groundwater table measured at a point is indicative for the available water storage, we do not have much information about the spatial distribution of groundwater storage due to lack of distributed observations and detailed hydrogeological information. In our subsequent analysis we consider deep groundwater data only, as we have longer time series available for this variable.

Gravity, being an integrated signal, contains information related to all kinds of simultaneous mass (re-) distributions. Thus, similar changes in groundwater storage do not necessarily cause similar gravity change. Depending on other (e.g., soil moisture) storage conditions, gravity change can be different for equal groundwater variation. As a result, we should not expect a unique relation between groundwater and gravity. We looked at moving-window cross correlation between groundwater and gravity with windows of varying length (from 1 day to 1 month) at 0–5-h lag. Looking at the histograms of the cross-correlation coefficients, we find both positive and negative high correlation, as well as no correlation (Fig. 4a).

In more than 50% of the cases there exists a high negative correlation ($\rho < -0.6$) between deep groundwater and gravity. The deep groundwater normally has a negative correlation with gravity because it is highly correlated with near-surface water storages (soil moisture, etc.), which have more mass variability than deep groundwater and generally lay above the gravimeter in the area. The high positive correlation or no correlation demonstrates a seasonal pattern. It is mainly during winter months (November–February) that we see either high positive correlation or no correlation at all. We looked at average hydrometeorological conditions (groundwater, temperature, precipitation) of the cross-correlation windows (Figs. 4b and 4c). At the time of high positive correlation or no correlation, average temperature is lower. A possible explanation for the high positive correlation during cold periods could be related to different dynamics in the soil moisture caused by freezing of the upper soil layer or by the vegetation using less water from the soil moisture. A frozen layer would decrease the evapotranspiration and slow down the redistribution processes. As the rate of transpiration is influenced by factors such as humidity and temperature, during cold (low temperature) and wet (high humidity) winter months there would be much less transpiration from the spruce trees in the catchment. As a result, water uptake from the soil moisture would be considerably lower, making the soil moisture storage less dynamic. Thus, when freezing temperatures limit soil moisture changes, variations in deep groundwater storage, which generally lays below the gravimeter in the area, dominate the mass (gravity) signal.

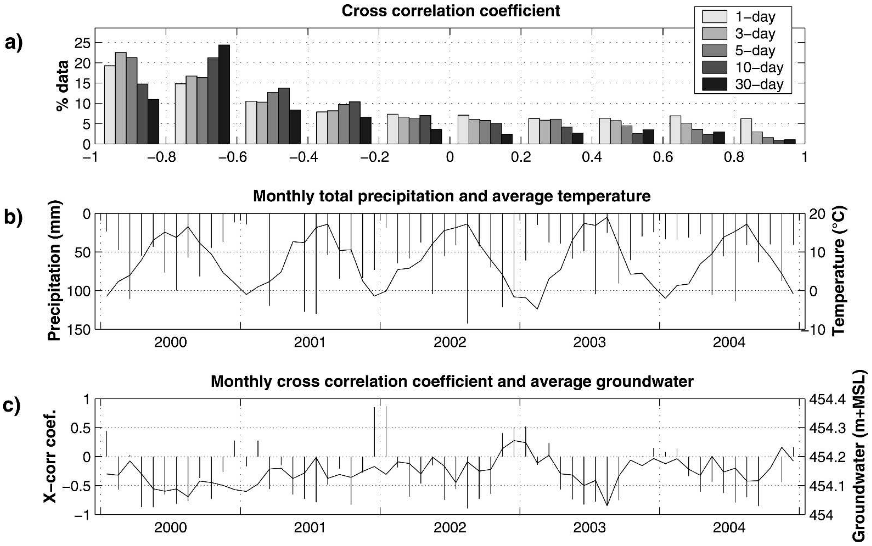

FIG. 4. Exploring groundwater and gravity. (a) Windowed lag-0 cross correlation between groundwater and gravity for windows of different time length. (b) Monthly average precipitation (bars) and temperature (line). (c) Monthly correlation between groundwater and gravity residual (bars) and average groundwater table (line).

The above-described time series analysis does not directly consider any hydrological-process-induced gravity change. To account for hydrological processes present in our catchment, we need to apply hydrological models to model gravity changes. The next section deals with the application of a distributed hydrological model to compute gravity variation.

4. Modeling gravity variation

To evaluate the ability to explain gravity residuals by means of distributed hydrological modeling we apply the SMR model to track temporal changes in near-surface storage in the catchment around the gravimeter. The SMR model (Boll et al. 1998; Frankenberger et al. 1999) provides distributed predictions of surface runoff and soil moisture and keeps track of interception store and storage in snow cover. The model tracks the flow in and out of grid cells of the soil layer using a basic mass balance [Eq. (2)]:

$$D_i \frac{d\theta_i}{dt} = P - \mathrm{ET}_i + \sum Q_{\mathrm{in}.i} - \sum Q_{\mathrm{out}.i} - L_i - R_i, \tag{2}$$

where i is cell address, D_i is depth to restrictive layer of the cell, θ_i is average soil moisture content of the cell, P is precipitation (throughfall and snowmelt), ET_i is actual evapotranspiration, $Q_{\mathrm{in}.i}$ is lateral inflow from neighboring upslope cells, $Q_{\mathrm{out}.i}$ is lateral outflow to neighboring downslope cells, L_i is downward leakage to bedrock (percolation), and R_i is surface runoff. Note that all the volumetric quantities are presented per area of a grid cell.

Calculation of the water balance is facilitated by a GIS, which keeps track of catchment characteristics such as elevation, soil properties, slope, land use, and flow direction as well as the moisture stored in each cell at each time step. In this study, the modeling time step is 1 h. Although the land use is mainly spruce forest, we distinguish the observatory area and the riparian zone from the main land use type. Being closest to the gravimeter the observatory area has the biggest effect on gravity, and that needs to be modeled carefully. The area (≈100 m × 100 m) around the observatory does not have trees and the roof over the gravimeter has a soil depth of 2.5 m with higher rock percentage. The riparian zone is modeled with less porosity in order to facilitate more surface runoff than that of average soil cover. Modifications to the original SMR model include the addition of a canopy layer to simulate interception and calculation of gravity variation based on moisture storage in the canopy, snow, and soil.

Based on Newton's law of gravitation in a local Cartesian coordinate system, the vertical component of gravitation (gravity anomaly) at location r due to a disturbing mass at location r' is computed by

$$\Delta g(r) = G \iiint_{v} \frac{\Delta\rho(r')(z' - z)}{|r' - r|^3}\, dv, \tag{3}$$

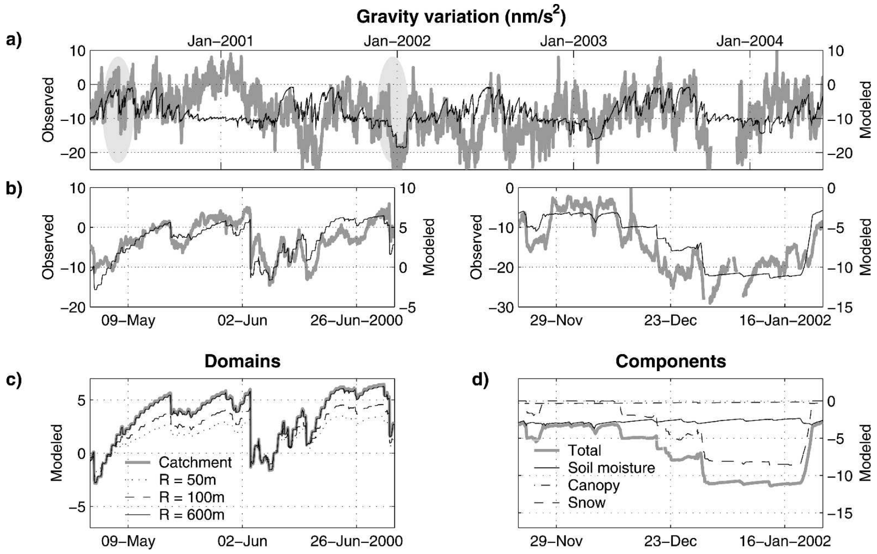

FIG. 5. Modeling gravity variation. (a) Observed (gray) and modeled (black) gravity variation. Model includes gravity variation due to soil moisture, snow, and canopy storage. Shaded areas are zoomed in and shown in *b*. (b) Zoomed version of *a*. (c) Effects of different domains in a small time window; *R* is domain radius. (d) Effects of different components in a small time window. Note different scales for observed and modeled variation in *b*, *c*, and *d*.

with the density difference $\Delta\rho$ of the disturbing mass relative to its surrounding, and the volume element $dv = dx'\ dy'\ dz'$.

Closed-form solutions of Eq. (3) are available for a multitude of simple bodies with constant density (Torge 1989). We used rectangular prisms (Nagy 1966) with horizontal limits defined by the pixel size in the digital elevation model (DEM) (20 m × 20 m) and vertical limits of soil depth for soil moisture, snow depth for the snow layer, and canopy interception storage depth for the canopy layer.

The SMR model for the Silberleite catchment was set up from available datasets (DEM, land use, and soil depths). Proper model calibration was hampered because of lack of good-quality runoff data. We checked the SMR model results for consistency in computed water balance components and estimated monthly runoff. In general, the model water balance is in agreement, for example, with estimates of evaporation/precipitation ratio of 0.5 (Peixoto and Oort 1992). Monthly runoff was estimated from available surface-water-level data and compared to modeled monthly runoff. While judging this verification, we have to keep in mind that no data were collected during high discharge and the fact that our model does not have a deep groundwater component; therefore, regional base flow contribution to total runoff at the weir is not simulated. However, the simulated runoff pattern was more or less in agreement with the observed flow pattern.

Figure 5a compares the observed gravity residuals for a 4-yr period (April 2000–May 2004) with the modeled gravity changes based on spatiotemporal simulations of the water balance components in the catchment. We model the change in gravity, which is then cumulated to a gravity residual. The observed gravity residual has a number of data gaps, and it cannot be claimed that the residuals are only due to hydrological changes. In comparing the observed gravity residuals and modeled gravity variation, our focus is mainly on the dynamic pattern of the signals. In general, we can reproduce the observed patterns quite well, although the dynamic range of modeled gravity variation is about 50% of observed gravity residuals. One possible reason could be that the modeled influence zone of mass distribution around the gravimeter underestimates the true influence zone, due to the fact that groundwater dynamics are poorly represented in the hydrological model. If we check the range of gravity variation caused by maximum soil moisture variability (difference between dry and saturated soil condition in the catchment), we find that the soil moisture variability alone cannot explain the observed gravity variation.

Figure 5c shows the effect of the domain size considered in gravity calculation. For calculation of gravity variation, storage change in each pixel of the total catchment was considered. To analyze the effect of the domain size, we considered circular domains of different radius around the gravimeter. In Fig. 5c it is obvious that the domain of total catchment and of the circle of 600-m radius (≈40% of the total catchment) around the gravimeter show the same dynamic range of gravity variation.

Figure 5d shows the effect of different components (soil moisture, snow and canopy storage) considered in gravity calculation. As expected, change in canopy storage does not have much influence on changing gravity. During cold periods, gravity variation due to change in soil moisture storage is rather low, compared to change in snow storage. Gravity variation due to change in snow storage does improve our model.

Although the general patterns of observed residuals and modeled variation are in good agreement, we experience some periods where modeled variations do not follow the pattern of observed residuals. The time periods, when the modeled gravity variations do not follow the observed pattern, are mainly the winter months (November–February), during which we can expect different dynamics in the saturated and unsaturated zones. In the time series analysis, we have seen high positive correlation between deep groundwater and gravity residuals during the same winter months, when modeled variation does not follow the observed pattern. The SMR model confirms less dynamics in the unsaturated zone during the winter months, when the relation between deep groundwater and gravity residuals switches from negative to positive or no correlation (section 3b).

5. Discussion

In this paper, both time series analysis and distributed hydrological modeling techniques are explored to explain local gravity variation as observed by a superconducting gravimeter at the Geodynamics Observatory Moxa, Germany. Both approaches yield encouraging results and serve complementary objectives. Time series modeling provides us with a simple yet effective technique to correct for precipitation effects on short-term gravity residuals. Analysis of deep groundwater and gravity residuals demonstrates different dynamics present in the catchment. Distributed water balance modeling explains both short and long-term behavior of the gravity signal. The hydrological model also confirms the findings from our time series analysis.

The periods (winter months: November–February) of high positive correlation between groundwater and gravity changes coincide with the periods where modeled gravity variations do not behave as observed gravity residuals. This study shows that the application of a distributed hydrological model can be useful in modeling gravity residuals. More hydrogeological and geophysical investigations are already being carried out, and the knowledge gained will be applied in extending the existing model.

From a hydrological perspective, terrestrial gravity measurements of the kind used in our study offer an intriguing new look at catchment-scale hydrological processes.

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