



**Data assimilation of
GRACE terrestrial
water storage
estimates**

N. Tangdamrongsub et al.

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

Data assimilation of GRACE terrestrial water storage estimates into a regional hydrological model of the Rhine River basin

N. Tangdamrongsub¹, S. C. Steele-Dunne², B. C. Gunter^{1,3}, P. G. Ditmar¹, and A. H. Weerts^{4,5}

¹Department of Geoscience and Remote Sensing, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands

²Department of Water Resources, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands

³School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, USA

⁴Operational Water Management, Deltares, Delft, the Netherlands

⁵Hydrology and Quantitative Water Management Group, Department of Environmental Sciences, Wageningen University, Wageningen, the Netherlands

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Received: 26 September 2014 – Accepted: 8 October 2014 – Published: 24 October 2014

Correspondence to: N. Tangdamrongsub (n.tangdamrongsub@tudelft.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

HESSD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

The ability to estimate Terrestrial Water Storage (TWS) realistically is essential for understanding past hydrological events and predicting future changes in the hydrological cycle. Inadequacies in model physics, uncertainty in model land parameters, and uncertainties in meteorological data commonly limit the accuracy of hydrological models in simulating TWS. In an effort to improve model performance, this study investigated the benefits of assimilating TWS estimates derived from the Gravity Recovery And Climate Experiment (GRACE) data into the OpenStreams-wflow model using an Ensemble Kalman Filter (EnKF) approach. The study area chosen was the Rhine River basin, which has both well-calibrated model parameters and high-quality forcing data that were used for experimentation and comparison. Four different case studies were examined which were designed to evaluate different levels of forcing data quality and resolution including those typical of other less well-monitored river basins. The results were validated using in situ groundwater and stream gauge data. The analysis showed a noticeable improvement in groundwater estimates when GRACE data were assimilated, with an overall improvement of up to 71 % in correlation coefficient (from 0.31 to 0.53) and 35 % in RMS error (from 8.4 to 5.4 cm) compared to the reference (ensemble open-loop) case. Only a slight overall improvement was observed in streamflow estimates when GRACE data were assimilated. Further analysis suggested that this is likely due to sporadic short terms, but sizeable, errors in the forcing data and the lack of sufficient constraints on the soil moisture component. Overall, the results highlight the benefit of assimilating GRACE data into hydrological models, particularly in data-sparse regions, while also providing insight on future refinements of the methodology.

HESSD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



1 Introduction

Terrestrial Water Storage (TWS) is the integrated sum of all surface water, soil moisture, snow water, and groundwater availability, and is a metric critical for the monitoring the water supply for domestic, industrial, and agricultural sectors. The ability to estimate TWS is useful for understanding past events and predicting future changes in the hydrological cycle, streamflow and water availability, as well as their impact on the occurrence of droughts, heat waves, and floods (Hirschi et al., 2007). The individual components of TWS influence the climate system in different ways. Soil moisture is a major source of water for the atmosphere in the terrestrial water cycle (Jung et al., 2010) and plays a particularly important role in the climate system (Seneviratne et al., 2010). Soil moisture estimates are also useful for seasonal predictions, and have been shown to improve predictions of air temperature in North America (Koster et al., 2010) and Europe (van den Hurk et al., 2012). Similarly, realistic estimation of the snowpack can improve the prediction of near surface temperature at high latitude regions at 15–30 day scales (Orsolini et al., 2013). Finally, groundwater variability influences soil moisture and evapotranspiration, and is related to long-term water availability and climate changes (Bierkens and van den Hurk, 2007; Green et al., 2011).

Despite the importance of having reliable estimates of TWS, knowledge about the spatial and temporal variations of TWS, and its components is generally lacking. This is particularly true at large scale, due to the absence of global monitoring systems. Ground-based measurements, while very accurate, only provide point-wise estimates (Dorigo et al., 2011; Lettenmaier and Famiglietti, 2006). Large spatial coverage can be achieved using satellite remote sensing observations, but these often measure only one component of the total storage and suffer from additional limitations. For example, in the case of soil moisture, satellite observations are limited to top few centimetres of the soil column and to areas free from dense vegetation cover (e.g. de Jeu et al., 2008; Entekhabi et al., 2010; Kerr et al., 2012). Variations in surface water can

HESSD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



be observed with satellite altimetry but this technique is currently limited to large target areas (e.g. Güntner et al., 2008).

Since measurements alone are not sufficient to comprehensively monitor all components of TWS, hydrological models are often employed. A strong point of hydrological models is their ability to obtain spatially distributed estimates, differentiate TWS components, and simulate changing boundary conditions. Many hydrological models are available, which vary in terms of process description, temporal resolution, spatial resolution, and the detail in process representation (Koster et al., 2000; Rodell et al., 2004). Models vary in terms of which TWS components are included in the model, and how they are represented. The performance of hydrological models is also influenced by the accuracy of the input forcing data and the quality of the model calibration. The existence of model uncertainties motivates the need to combine the model with independent observations to obtain a better representation of the system's behaviour.

Changes in TWS can also be estimated by observing variations of the regional gravity field over time. The idea is that changes in water storage, including those deep underground, induce a gravitational signature proportional to the amount of (water) mass redistribution. Since 2002, these variations have been measured by the Gravity Recovery and Climate Experiment (GRACE) satellite mission (Tapley et al., 2004). GRACE allows temporal variations of the Earth gravity field to be observed at spatial scales ranging in the hundreds of kilometres, and at time scales as short as one month. As part of the GRACE data processing, atmospheric and ocean related time-variable gravity effects are removed from the data, leaving the remaining gravity signal over the continents mostly representing changes in TWS (in some areas, additional removal of other nuisance signals is needed, such as those due to glacier melting, glacial isostatic adjustments, and megathrust earthquakes). The GRACE mission has enabled the first direct observations of large-scale TWS, and studies to date have shown high correlation with modelled TWS in terms of seasonal dynamics and regional spatial patterns (Syed et al., 2008; Becker et al., 2011; Longuevergne et al., 2013). A unique feature of satellite gravimetry is that it observes the total column of mass variations (including

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

groundwater) while other remote sensing techniques can only penetrate to a very limited depth, often just a few centimetres. In contrast to hydrological modelling, it is not possible to identify which layer the inferred mass variations can be attributed (Rodell et al., 2009).

Several earlier studies have employed data assimilation to combine the strengths of hydrological modelling and GRACE observations and to mitigate their respective weaknesses (Zaitchik et al., 2008; Su et al., 2010; Houborg et al., 2012; Li et al., 2012; Forman et al., 2012). In data assimilation, the model states are constrained by observations, taking into account the estimated uncertainties for both the model states and the observations (Evensen, 2003; Reichle, 2008). Employing data assimilation provides a mechanism to downscale the coarse GRACE TWS variations to the temporal and spatial resolution of the model as well as providing insight from the hydrological model into the distribution of TWS between the individual storage terms. Zaitchik et al. (2008) assimilated GRACE into the Catchment Land Surface Model to estimate the TWS over the Mississippi River Basin. Houborg et al. (2012) and Li et al. (2012) applied a similar strategy to improve the drought indicator over North America and Europe, respectively. Su et al. (2010) and Forman et al. (2012), extended the work of Zaitchik et al. (2008) to improve the estimated snow water equivalent over North America and northwestern Canada, respectively. All results from earlier studies reported that assimilating GRACE improved, or at least did not degrade, the hydrology model's performance. In particular, good agreements between estimated state variables, e.g. groundwater and streamflow, and the in situ measurements were observed. This study adds to these prior works by examining how GRACE assimilation performs when the hydrological model is not well calibrated or when unreliable meteorological data are used to force the model. This focus of the study is on the Rhine River basin (Fig. 1), which is significantly smaller than the large basin or continent scale studies of these prior works, so the analysis presented here provides new insight into the performance of GRACE assimilation over smaller basins. And, while previous data assimilation studies have been performed in the Rhine and neighbouring basins (e.g. Weerts and Serafy, 2006; Rakovec et al.,

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

These storage terms are calculated in the soil moisture and runoff response routines. Figure 2b shows the simulated SM, UZ and LZ from a nominal model run (i.e. using the calibrated parameters and local forcing data, see later). The main source of TWS variation in this model is SM, with the variations in LZ and UZ an order of magnitude smaller.

The key parameters of the soil moisture and runoff response routines are listed and described in Table 1. The OpenStreams-wflow model was calibrated for the Rhine river basin using observations from in situ streamflow gauges (Mülders et al., 1999; Eberle et al., 2002, 2005; Photiadou et al., 2011). The spatial distribution of the calibrated model parameters is shown in Fig. 3. In data-sparse regions, a lack of in situ (meteorological and streamflow) data makes it difficult to calibrate hydrological models (Sivapalan et al., 2003; Hrachowitz et al., 2013). Therefore, we decided to add “non-calibrated” cases to our simulations. In those cases, we defined the non-calibrated parameters as the areally-averaged values of the calibrated parameters in the entire basin, and used these for every grid cell in the basin.

3 Datasets

3.1 GRACE observation

The most recent release (RL05) of the GRACE gravity model product, generated by the University of Texas at Austin’s Center of Space Research (CSR: Bettadpur, 2012), was used in the analysis. The CSR RL05 models represent a time-series of Stokes coefficients up to a maximum spherical harmonic degree and order of 60, and are provided monthly. Following the GRACE conventional processing steps, degree-1 coefficients provided by Swenson et al. (2008) were added, and the degree-2 coefficients were replaced by the values estimated from satellite laser ranging (Cheng and Tapley, 2004). Variations in the gravity field were computed by removing the long-term mean (computed over the entire study period, see Sect. 5) from each monthly solution. The TWS

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Assessment & Data set (ECA&D) and ENSEMBLE project, known as E-OBS data (Haylock et al., 2008). Data collected from several hundred ground stations were combined to produce a daily grid of precipitation and mean surface temperature at a 0.25° spatial resolution. Local PET data were derived from climatological data obtained from the Commission for the Hydrology of the Rhine basin (CHR) and the German Meteorological Service (DWD) (Weerts et al., 2008). The daily local PET was interpolated from a monthly mean value with a fixed annual cycle and were available at a 1 km spatial resolution (Weerts et al., 2008; Photiadou et al., 2011).

Global precipitation and temperature data were obtained from Sheffield et al. (2005). These data are constructed based on the long-term near-surface meteorological variables from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP/NCAR) reanalysis product. The daily global precipitation and temperature data were provided at a spatial resolution of 0.5°. For global PET, the 1° daily product generated by Senay et al. (2008) was used.

Figure 4 shows a comparison between mean daily precipitation, temperature and PET in 2006 from the local and global forcing datasets. For the mean temperature, aside from the resolution difference, the spatial distribution and magnitude is very similar between the two datasets. On the other hand, significant differences can be seen between the local and global precipitation data, especially over the High Rhine. Differences are also observed in the PET products, with the global dataset having generally higher values than the local one, in addition to the much coarser spatial resolution of the global product.

3.3 Validation data

Groundwater and streamflow measurements from various networks are used to validate our estimated results.

In situ groundwater measurements were obtained from 3 different networks:

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1. Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen; (<http://www.elwasweb.nrw.de>, last access: 5 March 2014)
2. Bayerisches Landesamt für Umwelt (<http://www.gkd.bayern.de>, last access: 5 March 2014);
3. Portail national d'Accès aux Données sur les Eaux Souterraines (ADES, <http://www.ades.eaufrance.fr>, last access: 17 March 2014).

Measurements that did not exhibit seasonal variations were flagged as belonging to confined aquifers, and were excluded. Data from stations with weekly measurements (e.g. ADES) were interpolated to daily intervals. A total of eighteen wells were used for validation. Their locations are shown in Fig. 1, and their names are provided in Table A1.

The in situ groundwater measurements were provided in the form of piezometric head. The variations in piezometric head can be related to variations in groundwater storage if the specific yield is known (Rodell et al., 2007). As the latter data were unavailable, the piezometric head was scaled to the units of GW storage based on other GW data. Previous studies have demonstrated that subtracting SM derived from GLDAS from GRACE was able to extract the groundwater component from GRACE in several regions e.g. North America (Rodell et al., 2006, 2007), Australia (Tregoning et al., 2012), the Middle East (Longuevergne et al., 2013), etc. The variation in SM from GLDAS (ΔSM_{GLDAS}) was computed by removing the long-term mean value over the same period as the GRACE observations (see Sect. 5). The groundwater variations from GRACE (ΔGW_{GRACE}) were obtained by removing ΔSM_{GLDAS} from the GRACE observations every month. ΔGW_{GRACE} was interpolated to daily values in order to compare it to the daily head variations Δh using the following relationship:

$$\Delta GW_{GRACE} + e = a + b \cdot \Delta h \quad (1)$$

one month, while the OpenStreams-wflow model has a daily time step. In this study, it is assumed that the average TWS corresponds to the middle of the month. Spline interpolation between consecutive months is used to generate a time series of GRACE TWS variations at five-day intervals. In order to convert GRACE variations to absolute values the mean TWS in the study period was calculated from the nominal OpenStreams-wflow run and added to the GRACE time series.

GRACE observes total TWS, some components of which can be neglected (e.g. nominal OpenStreams-wflow simulations indicate that surface water and interception storage contributed by less than 1 % to the estimated TWS). However, dry snow is significant, particularly over the Alps (approximately 7 % to the estimated TWS over High Rhine). Therefore, the dry snow contribution was estimated from the nominal run of OpenStreams-wflow and removed from the GRACE observations prior to assimilation.

In the EnKF, the TWS is updated at each 1 km grid cell every five days. After each update, the increment in TWS must be distributed among the three stores. Here, the increment is used to adjust the SM first, subject to the upper and lower limits of zero and f_c . Any remaining increment is applied in turn to LZ and UZ. This order is based on the magnitude of the variations observed in Fig. 1 and also on the structure of the OpenStreams-wflow model; the upper zone has no upper limit and acts as a transient store between SM and LZ.

Similar to Zaitchik et al. (2008) and Houborg et al. (2012), an observation error of 20 mm was assumed for the GRACE observations based on the analyses of Wahr et al. (2006) and Klees et al. (2008).

4.3 Uncertainty in model forcing data and parameters

In the EnKF, stochastic noise can be included in model forcing data and parameters to account for model uncertainty. An earlier sensitivity study (Widiastuti, 2009) was conducted to identify the parameters of the OpenStreams-wflow model that had a significant impact on TWS. Six such parameters, which include f_c , l_p , β , $cflux$, khq , and $perc$

HESSD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



HESSD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

were found. Therefore, the soil moisture routine parameters, f_c , l_p and β , as well as the runoff routine parameters, c_{flux} , kh_q and $perc$, were perturbed. For the “calibrated” case, the calibrated model parameters in each grid cell were perturbed using additive Gaussian noise, with a mean of zero and a standard deviation (SD) equal to 10 % of the range of values that occurred over the whole Rhine basin. In the “non-calibrated” case, the mean parameter value in each grid cell was set to the average calibrated value across the whole basin, and the SD was set to that of the calibrated parameter across the whole basin. This was considered as a proxy for assigning approximate values based on soil and land type or climatology in a data-sparse region. The meteorological forcing data were also varied, with the temperature data being perturbed with additive Gaussian noise, and the precipitation and PET being perturbed with additive lognormal noise. In the “local forcing data” case, noise with SD based on 10 % of the nominal value was added to precipitation while 15 % noise was added to temperature and PET. For the “global forcing data” case, we assumed that the local forcing data were accurate and reliable, and the differences between the local and global forcing data represent the SD values (of global forcing data). The errors were assumed to be spatially correlated, so an exponential correlation function was applied to the covariance matrix for each variable. The correlation lengths for precipitation, temperature and PET were determined using variogram analysis (Widiastuti, 2009) and found to be 21, 21, and 59 km, respectively.

Recall from Sects. 1 and 3.2, that four cases are considered in this study: (1) calibrated parameters with local forcing data (CL), (2) calibrated parameters with global forcing data (CG), (3) non-calibrated parameters with local forcing data (NCL), and (4) non-calibrated parameters with global forcing data (NCG). Comparison of the four scenarios provides insight into the benefit of GRACE assimilation under different degrees of uncertainty. The lowest and highest levels of uncertainty are associated with the CL and the NCG cases.

5 Results and discussion

Using the EnKF approach described above, GRACE observations were assimilated into the OpenStreams-wflow model. An ensemble of 100 model states was propagated forward from 1 January 2001 to 30 November 2003 to spin up the model. The ensemble state at the end of the spin-up period provided the initial state for the assimilation. The study period is from 1 December 2003 to 31 October 2007 because the observed streamflow was only available until Autumn 2007.

5.1 Impact of GRACE assimilation on TWS estimates

First, the impact of assimilating GRACE on the temporal and spatial patterns of the estimated TWS is considered. For the temporal pattern, the areal mean of the estimated TWS over the entire Rhine River basin was computed. The time series of TWS variations from the ensemble open loop (EnOL, ensemble run without GRACE assimilation), EnKF, and GRACE observations are shown in Fig. 5.

As expected, there is a seasonal cycle in the TWS estimates, which varies between ± 75 mm. The high frequency variations in TWS in the CL and NCL that are not apparent in CG and NCG are due to the coarser spatial resolution of the global precipitation product. During the summer of 2006 (June, July, August: JJA), the areal mean global and local precipitation and temperature products agree. However, the global PET product estimates an areal mean PET of 4.10 mm while the local PET data suggest it was 2.89 mm. As the result, the minimum TWS in the CL and NCL cases in the EnOL is -69 mm while CG and NCG are close to -90 mm. In this period, GRACE assimilation has little impact on CL and NCL, but results in a significant (25 mm) update in TWS in the CG and NCG cases. The largest difference between the EnOL and EnKF occurs when TWS is increasing (for example, October 2005). This is apparent in all cases, but is greatest in the two non-calibrated cases. In all cases, Fig. 5 shows that assimilation draws the TWS estimate toward the GRACE observation.

HESSD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

The impact of GRACE assimilation also varies within the basin. Figure 6 shows the spatial distribution of the average increment (posterior minus prior) in TWS during winter (December, January, February: DJF, 2005–2006) and summer (JJA) of 2006. During the winter (left), the EnKF estimated wetter conditions over entire Rhine River basin when the local forcing data were used. In the Alps, the global precipitation product is approximately 35 % higher than the local precipitation product. Therefore, GRACE assimilation reduced the TWS estimate over the Alps in the CG and NCG cases. During the summer (right), GRACE assimilation reduced the TWS estimate over the Alps and Lahn basin when local forcing data were applied, but adds moisture in the global data case. In this period, the local PET product is 66 % lower than the global product over the Alps and 44 % lower over the Lahn basin. This is consistent with the increase in areal averaged TWS observed in the CG and NCG cases in Fig. 5. Since the local precipitation data are generally considered to be more accurate, the adjustment of the TWS estimates towards those produced by the local product is an excellent example of the benefit of GRACE assimilation, particularly in data sparse areas.

In the Regnitz basin (east of domain), GRACE assimilation leads to a significant increase in TWS in both calibrated cases during the winter months. In this basin, the upper zone recession coefficient (khq) is 0.52 in the calibrated case, compared to 0.3 in the non-calibrated case. This results in almost twice as much fast runoff in the calibrated case, which depletes the terrestrial water storage in the winter months. GRACE assimilation adds moisture to the UZ and LZ stores, drawing the TWS closer to the GRACE observations.

In the summer, an average of 0.70 and 1.07 mm was removed in each update from the southern part of Moselle basin in the CL and CG cases, respectively (Fig. 6b and d), compared to 0.74 and 1.25 mm added per update in the NCL and NCG cases. In the two calibrated cases, the evaporation threshold value (the product of f_c and l_p) is approximately 11 % less than that in the non-calibrated cases. This leads to less soil evaporation and higher soil moisture in the calibrated cases. GRACE assimilation

reduces the SM in the calibrated cases, and increases it in the non-calibrated cases to draw the TWS closer to the GRACE observations in all cases.

5.2 Impact of GRACE assimilation on GW estimates

The TWS and GW variations from OpenStreams-wflow were computed at every grid cell. The estimates at the Sundern and A319C wells are shown in Figs. 7 and 8. The two stations represent the behaviour of the other 16 stations (detailed below). For example, stations 2, 3, 4, 6, 9, 10, 11, 13, and 18 have similar behaviour to Sundern, while the rest have similar behaviour to A319C station. Recall that GW is defined as the sum of UZ and LZ, so the difference between the left and right columns is the SM term. GRACE measures monthly variations, so the monthly mean of TWS, GW estimates and the in situ data are shown. Similar to the areal mean values, the TWS from the EnKF in the individual grid cells (left column) is generally between the values from the EnOL and those observed by GRACE.

At Sundern (Fig. 7) in the CG and NCG cases, the impact of the forcing data was seen in the summer of every year. Table 2 shows that the precipitation, temperature and PET at Sundern were higher in the global forcing data than in the local data. Figure 7c and g suggest that this leads to a more negative estimate of TWS in the EnOL for the CG and NCG cases. In the EnKF results, these TWS estimates are drawn towards the GRACE observations. The corresponding updates in terms of GW are larger in the global forcing data case than in the local forcing data cases – assimilation added approximately 5–10 mm of water to GW in the global data cases. Similar behaviour was also seen in CL and NCL cases in summer 2005.

At Sundern, the estimated GW in the CL case agrees quite well with the in situ values, suggesting that the distribution between the SM and GW components is reasonable in the calibrated cases. The fact that a good estimate of TWS does not result in an improved GW estimate indicates that the non-calibrated parameters are leading to an incorrect distribution of the TWS between the different stores. In the NCL and NCG cases, f_c is just 179 mm compared to the calibrated value of 239 mm. So, for the same

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



TWS value, the non-calibrated cases have more water in GW than the calibrated cases. As a result, despite the agreement in TWS in the winter months, the GW variation is considerably overestimated.

In every case at the A319C well location (Fig. 8), the EnOL estimated lower TWS in the first half of 2004 and 2006, and higher in the second half of the same years. Assimilation updated the TWS toward GRACE observation in these periods and resulted in better agreement between the assimilated and observed GW. In late-2005, the estimated TWS from the EnOL and EnKF are very close to the GRACE observations. However, the estimated GW in both cases is a lot lower than that observed in situ. As discussed, the difference between the two is soil moisture. The model is predicting a significant decline in soil moisture in all four cases. However, given there is little to improve in terms of TWS, the GW estimate from the EnKF is as bad as that from the EnOL.

The impact of the forcing data used is also presented. In CG and NCG cases, on 3 October and 23 October 2006, underestimated global precipitation caused the underestimated GW. GRACE could not correct such a high frequency event due to the limitation of its temporal resolution. The choice of the parameters plays a role in the estimated GW magnitude (as seen in Fig. 7), but now the non-calibrated parameters (compared to the calibrated ones) provided closer values to the in situ data (Fig. 8f and h). Higher non-calibrated fc parameter (see Table 3 for the values) was responsible for smaller GW estimates.

Tables 4 and 5 show the correlation coefficient and RMS error (RMSE) between the estimated and in situ GW for all eighteen well locations indicated on Fig. 1. These were calculated based on the monthly mean, but similar results were obtained using the daily values. In most cases, assimilation leads to an increase in correlation coefficient and a reduction in RMSE.

The results varied across the wells. The highest correlation coefficients in the EnOL simulations were typically found in the CL case, followed by the NCL. Clearly, using the local forcing data has a significant impact in resolving features at a single grid cell.

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



HESD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



An exception is the Main basin (wells 5, 7–10) where the global forcing data produce TWS more consistently with the GRACE observations and hence result in a better agreement with the GW. The highest correlation coefficients in the EnKF cases are also found in the two local data cases. The improvements in correlation coefficient are seen in all four cases. The CL and NCL cases also yield the lowest RMSE values in the EnOL case, and the results with the EnKF are very mixed.

It is important to note that at many wells, the NCL and NCG cases yield higher correlation coefficients than the CL and CG cases, respectively. Recall that the model is calibrated using streamflow, not groundwater data. So, while assimilation draws the modelled TWS towards the GRACE observations, the model parameters have a significant impact on whether or not this translates to an improvement in GW estimate.

One of the objectives was to examine the potential value of GRACE assimilation in data-sparse regions. In the NCG case, it is encouraging that GRACE assimilation consistently leads to an increase in correlation coefficient (up to 33%) and reduction in RMSE (up to 35%). In general though, assimilation of GRACE observations leads into an increase in correlation coefficient (up to 71%, at station 11 in the CG case) and a decrease in RMSE (up to 35%, at station 1 in the NCG case).

5.3 Impact of GRACE assimilation on streamflow estimates

The estimated and observed streamflows at Maxau (upstream) and Wessel (downstream) are shown in Figs. 9 and 10. Accurate forcing data, particularly precipitation, are essential for reproducing the observed streamflow. The high frequency variations in streamflow associated with fast response to local precipitation are often reproduced reasonably well in the CL case, but not in the CG case (compare Figs. 9a and b, 10a and b).

Use of the global data frequently underestimates the streamflow. This is clear on 5 June 2004, 24 August 2005, 6 October 2006, and 10 August 2007 in Fig. 9b and d. Comparing Fig. 9a to b, it is clear that the larger peaks in streamflow are poorly estimated when the global data are used. Because GRACE observations describe monthly

HESSD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

variations over a larger area, they can do little to capture these individual streamflow events. By correcting TWS, GRACE assimilation mainly influences the longer term variations. The difference between EnOL and EnKF is very small in the CL case. The largest differences are observed in the CG and NCG cases, where TWS is updated to correct for errors in forcing data (e.g. summer 2004 and 2006 in Fig. 9).

Figure 11 shows the impact of GRACE assimilation on the correlation coefficient, Nash–Sutcliffe coefficient (NS) (Nash and Sutcliffe, 1970), and RMSE in streamflow. Results are shown for four gauge stations along the main channel, as well as the average value across all thirteen stations. These results underscore the importance of forcing data and calibration for estimating streamflow. By far, the highest correlation coefficients and NS coefficients and lowest RMSEs are obtained when local forcing data are used. Use of global forcing data leads to a significant loss in performance. For example, using global rather than local forcing data with the calibrated model results in a decrease in correlation coefficient from 0.89 to 0.65, a decrease in NS coefficient from 0.76 to 0.35 and an increase in RMSE of 71 % in the EnKF results. Using the non-calibrated model rather than the calibrated model also leads to poorer performance, though to a lesser degree. For example, using the non-calibrated rather than calibrated model with the local forcing data results in a decrease in correlation coefficient from 0.89 to 0.88, a decrease in NS coefficient from 0.76 to 0.65 and an increase in RMSE of 23 % in the EnKF results.

Compared to the differences due to forcing data and calibration, GRACE assimilation leads to a relatively modest improvement in streamflow estimates. In terms of correlation coefficient, the largest improvements on average (Avg column) are found when the global forcing data are used. The correlation coefficient increased from 0.64 to 0.65 in the CG case, and 0.65 to 0.66 in the NCG case. The largest improvement at an individual station was found at Maxau where assimilation resulted in an increase in correlation coefficient from 0.54 to 0.59 in the NCG case.

Similarly, GRACE assimilation leads to a modest improvement in terms of NS coefficient. The largest average improvement was from 0.62 to 0.65 in the NCL case.

HESSD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

◀

▶

◀

▶

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



5 a groundwater model can be expected to yield better results in terms of groundwater variations. The issue of scale is also significant. GRACE observes monthly variations on the order of hundreds of kilometres. Groundwater variations can be influenced by local features at finer scales. Validation against a denser network of well data or an independent groundwater model could be used to determine if an improvement occurs at the scale of the entire basin. Due to the coarse resolution of the observations, GRACE assimilation resulted in only a modest improvement in streamflow estimates. Correlation coefficients increased by up to 2 %, NS coefficients increased by up to 4 % and RMSE was reduced by up to 4 %.

10 The second goal of this study was to investigate the potential value of assimilating GRACE observations in data-sparse regions. Results from four scenarios were compared in which the ensemble mean model parameters were either calibrated values, or basin average values and the meteorological forcing data were either local (high quality) data or global (poorer quality) data. By comparing the four cases, it was shown that GRACE assimilation could correct for errors in model forcing data and parameter calibration by drawing the estimated TWS toward that observed by GRACE. This also resulted in drawing the estimated groundwater storage closer to the in situ measurement. While this is of limited value in a river basin with existing high quality meteorological data and well-calibrated models, this indicates that GRACE could be combined with a hydrological model in a data-sparse region to yield additional insight into the variations in terrestrial water storage. In terms of streamflow, a comparison of the four scenarios demonstrates that the ability to capture high flow events was determined largely by the quality of the forcing data and the model parameters. The improvements in streamflow estimates after assimilation were modest. Nevertheless, we consider the obtained results as promising, particularly in data-sparse scenarios, e.g. the NCG case. They indicate that GRACE contains information that can be useful for streamflow estimation. Whether updating TWS is the best way to use this information is an open question. An alternative strategy could be to use GRACE assimilation

for parameter estimation at a sub-basin or basin scale and constrain the rainfall–runoff model through assimilation of soil moisture observations.

In conclusion, GRACE assimilation is clearly beneficial, particularly in data-sparse regions. In addition to improving the estimated streamflow, the TWS updates can provide insight into the behaviour of the hydrological model, its forcing data and parameters. Further research will combine assimilation of GRACE and a soil moisture remote sensing product to constrain the SM estimate storage term, and ensure that improved TWS would lead to more consistently improved estimates of groundwater storage variations. Further research will also explore the value of assimilating GRACE into a groundwater model in which the primary processes of interest vary on temporal and spatial scales similar to those of GRACE. In addition, future research should include more detailed spatial and temporal information on the GRACE observation error from the product itself. This could be particularly important in smaller basins like the Rhine, and can be used to account for the fact that the GRACE overpasses are irregular and may not observe TWS variations in response to specific events.

Acknowledgements. This research was funded by the Netherlands Organisation for Scientific Research, NWO (project number 842.00.006). The work of S. C. Steele-Dunne was supported by the NWO Veni Grant Program (ALW 863.09.015). We would like to thank Eric Sprokkereef Secretary of the International Commission for the Hydrology of the Rhine basin for granting permission for the use of hydrologic data. Jaap Schellekens (Deltares) is acknowledged for help with the OpenStreams model of the Rhine. The authors also want to thank Edwin Sutanudjaja for productive discussions about the groundwater data.

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



References

- Bader, S., Belz, J. U., Jakob, A., Mathis, C., Morf-Graf, S., Mürlebach, M., and Schürch, M.: International commission for the hydrology of the Rhine basin (CHR), edited by: Sprokkereef, E., Annual CHR report 2012, Lelystad, the Netherlands, 2013.
- 5 Becker, M., Meyssignac, B., Xavier, L., Cazenave, A., Alkama, R., and Decharme, B.: Past terrestrial water storage (1980–2008) in the Amazon Basin reconstructed from GRACE and in situ river gauging data, *Hydrol. Earth Syst. Sci.*, 15, 533–546, doi:10.5194/hess-15-533-2011, 2011.
- Bettadpur, S.: Insights into the Earth System mass variability from CSR-RL05 GRACE gravity fields, EGU Meeting, abstract #EGU2012-6409, Vienna, Austria, 2012.
- 10 Bierkens, M. F. P. and van den Hurk, B. J. J. M.: Groundwater convergence as a possible mechanism for multi-year persistence in rainfall, *Geophys. Res. Lett.*, 34, L02402, doi:10.1029/2006GL028396, 2007.
- Cheng, M. and Tapley, B.: Variations in the Earth's oblateness during the past 28 years, *J. Geophys. Res.*, 109, B09402, doi:10.1029/2004JB003028, 2004.
- 15 de Jeu, R. A. M., Wagner, W., Holmes, T. R. H., Dolman, A. J., van de Giesen, N. C., and Friesen, J.: Global Soil Moisture Patterns Observed by Space Borne Microwave Radiometers and Scatterometers, *Surv. Geophys.*, 28, 399–420, doi:10.1007/s10712-008-9044-0, 2008.
- Dorigo, W. A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Xaver, A., Gruber, A., Drusch, M., Mecklenburg, S., van Oevelen, P., Robock, A., and Jackson, T.: The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements, *Hydrol. Earth Syst. Sci.*, 15, 1675–1698, doi:10.5194/hess-15-1675-2011, 2011.
- 20 Eberle, M., Buiteveld, H., Beersma, J., Krahe, P., and Wilke, K.: Estimation of extreme floods in the river Rhine basin by combining precipitation-runoff modelling and a rainfall generator, in: Proceedings International Conference on Flood Estimation, Berne, CHR report II-17, International Commission for the Hydrology of the Rhine basin (CHR), Lelystad, the Netherlands, 2002.
- 25 Eberle, M., Buiteveld, H., Krahe, P., and Wilke, K.: Hydrological Modelling in the River Rhine Basin, Part III: Daily HBV Model for the Rhine Basin, Report 1451, Bundesanstalt für Gewässerkunde (BFG), Koblenz, Germany, 2005.
- 30

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Entekhabi, D., Njoku, E. G., O'Neill, P. E., Kellogg, K. H., Crow, W. T., Edelstein, W. N.,
Entin, J. K., Goodman, S. D., Jackson, T. J., Johnson, J., Kimball, J., Piepmeier, J. R.,
Koster, R. D., Martin, N., McDonald, K. C., Moghaddam, M., Moran, S., Reichle, R., Shi, J. C.,
Spencer, M. W., Thurman, S. W., Leung, T., and van Zyl, J.: The Soil Moisture Active Passive
(SMAP) mission, P. IEEE, 98, 704–716, doi:10.1109/JPROC.2010.2043918, 2010.

Evensen, G.: Sequential data assimilation with a non-linear quasi-geostrophic model using
Monte Carlo methods to forecast error statistics, J. Geophys. Res., 99, 10143–10162, 1994.

Evensen, G.: The ensemble Kalman filter: theoretical formulation and practical implementation,
Ocean Dynam., 53, 343–367, doi:10.1007/S10236-003-0036-9, 2003.

Forman, B. A., Reichle, R. H., and Rodell, M.: Assimilation of terrestrial water storage
from GRACE in snow-dominated basin, Water Resour. Res., 48, W01507,
doi:10.1029/2011WR011239, 2012.

Green, T. R., Taniguchi, M., Kooi, H., Gurdak, J. J., Allen, D. M., Hiscock, K. M., Treidel, H., and
Aureli, A.: Beneath the surface of global change: impacts of climate change on groundwa-
ter, J. Hydrol., 405, 532–560, doi:10.1016/j.jhydrol.2011.05.002, 2011.

Güntner, A.: Improvement of global hydrological models using GRACE data, Surv. Geophys.,
29, 375–397, doi:10.1007/s10712-008-9038-y, 2008.

Haylock, M. R., Hofstra, N., Klein Tank, A. M. G., Klok, E. J., Jones, P. D., and New, M.: A
European daily high-resolution gridded dataset of surface temperature and precipitation for
1950–2006, J. Geophys. Res., 113, D20119, doi:10.1029/2008JD010201, 2008.

Hirschi, M., Seneviratne, S. I., Hagemann, S., and Schär, C.: Analysis of seasonal terrestrial
water storage variations in regional climate simulations over Europe, J. Geophys. Res., 112,
D22109, doi:10.1029/2006JD008338, 2007.

Houborg, R., Rodell, M., Li, B., Reichle, R., and Zaitchik, B. F.: Drought indicators based on
model-assimilated Gravity Recovery and Climate Experiment (GRACE) terrestrial water stor-
age observations, Water Resour. Res., 48, W07525, doi:10.1029/2011WR011291, 2012.

Hrachowitz, M., Savenije, H. H. G., Blöschl, G., McDonnell, J. J., Sivapalan, M., Pomeroy, J. W.,
Arheimer, B., Blume, T., Clark, M. P., Ehret, U., Fencica, F., Freer, J. E., Gelfan, A.,
Gupta, H. V., Hughes, D. A., Hut, R. W., Montanari, A., Pande, S., Tetzlaff, D., Troch, P. A.,
Uhlenbrook, S., Wagener, T., Winsemius, H. C., Woods, R. A., Zehe, E., and Cudennec, C.:
A decade of Predictions in Ungauged Basins (PUB) – a review, Hydrolog. Sci. J., 58, 1198–
1255, doi:10.1080/02626667.2013.803183, 2013.

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Jekeli, C.: Alternative methods to smooth the Earth's gravity field, Rep. 327, Dept. of Geod. Sci., and Surv., Ohio State Univ., Columbus, 1981.
- Jung, M., Reichstein, M., Ciais, P., Seneviratne, S. I., Sheffield, J., Goulden, M. L., Bonan, G., Cescatti, A., Chen, J., de Jeu, R., Dolman, A. J., Eugster, W., Gerten, D., Gianelle, D., Gobron, N., Heinke, J., Kimball, J., Law, B. E., Montagnani, L., Mu, Q., Mueller, B., Olson, K., Papale, D., Richardson, A. D., Rouspard, O., Running, S., Tomelleri, E., Viovy, N., Weber, U., Williams, C., Wood, E., Zaehle, S., and Zhang, K.: Recent decline in the global land evapotranspiration trend due to limited moisture supply, *Nature*, 467, 951–954, doi:10.1038/nature09396, 2010.
- Karszenberg, D., Schmitz, O., Salamon, P., De Jong, K., and Bierkens, M. F. P.: A software framework for construction of process-based stochastic spatio-temporal models and data assimilation, *Environ. Modell. Softw.*, 25, 489–502, 2009.
- Kerr, Y. H., Waldteufel, P., Richaume, P., Wigneron, J. P., Ferrazzoli, P., Mahmoodi, A., Bitar, A. A., Cabot, F., Gruhier, C., Juglea, S. E., Leroux, D., Mialon, A., and Delwart, S.: The SMOS Soil Moisture Retrieval Algorithm, *IEEE T. Geosci. Remote*, 50, 1384–1403, doi:10.1109/TGRS.2012.2184548, 2012.
- Klees, R., Liu, X., Wittwe, T., Gunter, B. C., Revtova, E. A., Tenzer, R., Ditmar, P., Winsemius, H. C., and Savenije, H. H. G.: A comparison of global and regional GRACE models for land hydrology, *Surv. Geophys.*, 29, 335–359, doi:10.1007/s10712-008-9049-8, 2008.
- Koster, R. D., Suarez, M. J., Ducharne, A., Stieglitz, M., and Kumar, P.: A catchment-based approach to modeling land surface processes in a general circulation model, 1. Model structure, *J. Geophys. Res.*, 105, 24809–24822, 2000.
- Koster, R. D., Manhanama, S. P. P., Yamada, T. J., Balsamo, G., Berg, A. A., Boisserie, M., Dirmeyer, P. A., Doblus-Reyes, F. J., Drewitt, G., Gordon, C. T., Guo, Z., Jeong, J.-H., Lawrence, D. M., Lee, W.-S., Li, Z., Luo, L., Malyshev, S., Merryfield, W. J., Seneviratne, S. I., Stanelle, T., van den Hurk, B. J. J. M., Vitart, F., and Wood, E. F.: Contribution of land surface initialization to subseasonal forecast skill: first results from a multi-model experiment, *Geophys. Res. Lett.*, 37, L02402, doi:10.1029/2009GL041677, 2010.
- Landerer, F. W. and Swenson, S. C.: Accuracy of scaled GRACE terrestrial water storage estimates, *Water Resour. Res.*, 48, W04531, doi:10.1029/2011WR011453, 2012.
- Lettenmaier, D. P. and Famiglietti, J. S.: Water from on high, *Nature*, 444, 562–563, 2006.

**Data assimilation of
GRACE terrestrial
water storage
estimates**

N. Tangdamrongsub et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

- Li, B., Rodell, M., Zaitchik, B. F., Reichle, R. H., Koster, R. D., and van Dam, T. M.: Assimilation of GRACE terrestrial water storage into a land surface model: evaluation and potential value for drought monitoring in western and central Europe, *J. Hydrol.*, 446–447, 103–115, 2012.
- Lindström, G., Johansson, B., Persson, M., Gardelin, M., and Bergström, S.: Development and test of the distributed HBV-96 hydrological model, *J. Hydrol.*, 201, 272–288, 1997.
- Longuevergne, L., Wilson, C. R., Scanlon, B. R., and Crétaux, J. F.: GRACE water storage estimates for the Middle East and other regions with significant reservoir and lake storage, *Hydrol. Earth Syst. Sci.*, 17, 4817–4830, doi:10.5194/hess-17-4817-2013, 2013.
- Mülders, R., Parmet, B., and Wilke, K.: Hydrological Modelling in the river Rhine basin, final report, Report 1215, Bundesanstalt für Gewässerkunde (BFG), Koblenz, Germany, 1999.
- Nash, J. E. and Sutcliffe, J. V.: River flow forecasting through conceptual models part I – a discussion of principles, *J. Hydrol.*, 10, 282–290, 1970.
- Orsolini, Y. J., Senan, R., Balsamo, G., Doblas-Reyes, F. J., Vitart, F., Weisheimer, A., Carrasco, A., and Benestad, R. E.: Impact of snow initialization on sub-seasonal forecasts, *Clim. Dynam.*, 41, 1969–1982, doi:10.1007/s00382-013-1782-0, 2013.
- Peltier, W. R.: Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE, *Annu. Rev. Earth Planet. Sci.*, 32, 111–149, 2004.
- Photiadou, C. S., Weerts, A. H., and van den Hurk, B. J. J. M.: Evaluation of two precipitation data sets for the Rhine River using streamflow simulations, *Hydrol. Earth Syst. Sci.*, 15, 3355–3366, doi:10.5194/hess-15-3355-2011, 2011.
- Rakovec, O., Weerts, A. H., Hazenberg, P., Torfs, P. J. J. F., and Uijlenhoet, R.: State updating of a distributed hydrological model with Ensemble Kalman Filtering: effects of updating frequency and observation network density on forecast accuracy, *Hydrol. Earth Syst. Sci.*, 16, 3435–3449, doi:10.5194/hess-16-3435-2012, 2012.
- Reichle, R. H.: Data assimilation methods in the Earth sciences, *Adv. Water Resour.*, 31, 1411–1418, doi:10.1016/j.advwatres.2008.01.001, 2008.
- Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C. J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J. K., Walker, J. P., Lohmann, D., and Toll, D.: The global land data assimilation system, *B. Am. Meteorol. Soc.*, 85, 381–394, 2004.
- Rodell, M., Chen, J., Kato, H., Famiglietti, J. S., Nigro, J., and Wilson, C. R.: Estimating ground-water storage changes in the Mississippi River basin (USA) using GRACE, *Hydrogeol. J.*, 15, 159–166, 2007.

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Rodell, M., Velicogna, I., and Famiglietti, J. S.: Satellite-based estimates of groundwater depletion in India, *Nature*, 460, 999–1002, 2009.
- Schellekens, J.: OpenStream wflow documentation release 0.91, Deltares, <https://publicwiki.deltares.nl/display/OpenS/Installation+and+Download>, last access: 5 October 2013.
- 5 Senay, G. B., Verdin, J. P., Lietzow, R., and Melesse, A. M.: Global daily reference evapotranspiration modeling and evaluation, *J. Am. Water Resour. Assoc.*, 44, 969–979, doi:10.1111/j.1752-1688.2008.00195.x, 2008.
- Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A.: Investigating soil moisture-climate interactions in a changing climate: a review, *Earth-Sci. Rev.*, 99, 125–161, doi:10.1016/j.earscirev.2010.02.004, 2010.
- 10 Sheffield, J., Goteti, G., and Wood, E. F.: Development of a 50 yr high-resolution global dataset of meteorological forcings for land surface modeling, *J. Climate*, 19, 3088–3111, 2005.
- Sivapalan, M., Takeuchi, K., Franks, S. W., Gupta, V. K., Karambiri, H., Lakshmi, V., Liang, X., McDonnell, J. J., Mendiondo, E. M., O’Connell, P. E., Oki, T., Pomeroy, J. W., Schertzer, D., Uhlenbrook, S., and Zehe, E.: IAHS decade on predictions in ungauged basins (PUB) 2003–2012: shaping an exciting future for the hydrological sciences, *Hydrolog. Sci. J.*, 48, 857–880, 2003.
- 15 Su, H., Yang, Z.-L., Dickinson, R. E., Wilson, C. R., and Niu, G.-Y.: Multisensor snow data assimilation at the continental scale: the value of Gravity Recovery and Climate Experiment terrestrial water storage information, *J. Geophys. Res.*, 15, D10104, doi:10.1029/2009JD013035, 2010.
- Swenson, S. and Wahr, J.: Post-processing removal of correlated errors in GRACE data, *Geophys. Res. Lett.*, 33, L08402, doi:10.1029/2005GL025285, 2006.
- Swenson, S., Chambers, D., and Wahr, J.: Estimating geocenter variations from a combination of GRACE and ocean model output, *J. Geophys. Res.*, 113, B08410, doi:10.1029/2007JB005338, 2008.
- 25 Syed, T. H., Famiglietti, J. S., and Chambers, D.: GRACE-based estimates of terrestrial freshwater discharge from basin to continental scales, *J. Micrometeorol.*, 10, 22–40, doi:10.1175/2008JHM993.1, 2008.
- 30 Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F., and Watkins, M.: GRACE measurements of mass variability in the Earth System, *Science*, 305, 503–505, 2004.

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Tregoning, P., McClusky, S., van Dijk, A. I. J. M., Crosbie, R. S., and Peña-Arancibia, J. L.: Assessment of GRACE Satellites for Groundwater Estimation in Australia, National Water Commission, Canberra, 82 pp., 2012.
- van den Hurk, B., Doblus-Reyes, F., Balsamo, G., Koster, R. D., Seneviratne, S. I., and Camargo Jr., H.: Soil moisture effects on seasonal temperature and precipitation forecast scores in Europe, *Clim. Dynam.*, 28, 349–362, 2012.
- Wahr, J., Molenaar, M., and Bryan, F.: Time variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, 103, 30205–30229, 1998.
- Wahr, J., Swenson, S., and Velicogna, I.: Accuracy of GRACE mass estimates, *Geophys. Res. Lett.*, 33, L06401, doi:10.1029/2005GL025305, 2006.
- Weerts, A. H. and Serafy, G. Y. H.: Particle filtering and ensemble Kalman filtering for state updating with hydrological conceptual rainfall–runoff models, *Water Resour. Res.*, 42, W09403, doi:10.1029/2005WR004093, 2006.
- Weerts, A. H., Meißner, D., and Rademacher, S.: Input Data Rainfall–Runoff Model Operational Systems FEWS-NL & FEWS-DE, Tech. rep., Deltares, 2008.
- Widiastuti, E.: Data assimilation of GRACE terrestrial water storage data into a hydrological model using the ensemble Kalman smoother: a case study of the Rhine river basin, M.S. thesis, TU Delft, Delft, the Netherlands, 2009.
- Zaitchik, B. F., Rodell, M., and Reichle, E. H.: Assimilation of GRACE terrestrial water storage data into a land surface model: results for the Mississippi basin, *Am. Meteor. Soc., J. Hydrometeorol.*, 9, 535–548, 2008.

HESSD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)**Table 1.** Parameters of the soil moisture and runoff routines in the OpenStreams-wflow model.

Parameter	Description	Unit
fc	Maximum soil moisture storage	mm
β	Empirical based parameter determines the relative contribution to runoff from soil moisture storage	–
cflux	Maximum value of capillary rise from upper zone storage to soil moisture storage	mm day ⁻¹
khq	Recession constant of upper zone storage, determines the amount of quick runoff from upper zone storage	day ⁻¹
perc	Maximum percolation value (from upper to lower zone storage)	mm day ⁻¹
lp	Soil moisture fraction above which actual evapotranspiration (ET) equals potential ET	–
k4	Recession constant of lower zone storage, determines the amount of baseflow from lower zone storage	day ⁻¹
α	Non-linearity parameter of upper zone storage	–

HESSD

11, 11837–11882, 2014

**Data assimilation of
GRACE terrestrial
water storage
estimates**

N. Tangdamrongsub et al.

Table 2. Daily mean values of the forcing data at Sundern during summer (JJA) months.

	Precipitation (mm)		Temperature (°C)		PET (mm)	
	Local	Global	Local	Global	Local	Global
2004	5.48	5.21	16.10	17.65	2.47	3.30
2005	5.25	4.68	16.12	17.46	2.47	3.55
2006	4.96	4.39	17.64	19.25	2.47	3.90
2007	9.97	7.08	16.09	17.52	2.47	3.25

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Table 3. Ensemble mean parameter values at the Sundern, and A319C well locations for the calibrated and non-calibrated simulations.

Parameter	Sundern		A319C	
	Calibrated	Non-calibrated	Calibrated	Non-calibrated
<i>fc</i>	239.03	179.12	130.95	181.98
β	2.06	1.65	1.95	1.68
<i>cflux</i>	0.06	0.27	0.41	0.30
<i>khq</i>	0.10	0.12	0.06	0.09
<i>perc</i>	0.67	1.15	0.43	1.09
<i>lp</i>	0.88	0.75	0.67	0.72
<i>k4</i>	0.63	0.03	0.01	0.03

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)

[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 4. Correlation coefficient computed between monthly mean estimated GW variation and monthly mean in situ variation. Names of the stations (first column) are provided in Table A1.

	CL		CG		NCL		NCG	
	EnOL	EnKF	EnOL	EnKF	EnOL	EnKF	EnOL	EnKF
1	0.85	0.83	0.71	0.74	0.79	0.85	0.70	0.78
2	0.57	0.68	0.32	0.52	0.43	0.65	0.38	0.45
3	0.69	0.81	0.46	0.68	0.51	0.73	0.46	0.61
4	0.60	0.67	0.42	0.58	0.50	0.75	0.60	0.67
5	0.71	0.68	0.67	0.76	0.71	0.72	0.72	0.78
6	0.57	0.64	0.58	0.66	0.74	0.78	0.66	0.72
7	0.77	0.80	0.67	0.71	0.80	0.83	0.64	0.72
8	0.75	0.80	0.65	0.78	0.81	0.83	0.62	0.74
9	0.50	0.64	0.54	0.70	0.72	0.78	0.65	0.80
10	0.56	0.58	0.50	0.55	0.66	0.70	0.42	0.46
11	0.41	0.55	0.31	0.53	0.71	0.73	0.72	0.74
12	0.71	0.80	0.64	0.71	0.76	0.85	0.74	0.78
13	0.77	0.80	0.50	0.56	0.72	0.84	0.59	0.66
14	0.71	0.70	0.73	0.74	0.33	0.47	0.51	0.56
15	0.82	0.85	0.67	0.69	0.72	0.83	0.65	0.71
16	0.68	0.80	0.55	0.64	0.77	0.88	0.63	0.71
17	0.67	0.79	0.55	0.60	0.70	0.82	0.57	0.66
18	0.65	0.66	0.64	0.65	0.45	0.54	0.59	0.63
Mean	0.67	0.73	0.56	0.66	0.66	0.75	0.60	0.68

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 5. RMSE [mm] computed between monthly mean estimated GW variation and monthly mean in situ variation. Names of the stations (first column) are provided in Table A1.

	CL		CG		NCL		NCG	
	EnOL	EnKF	EnOL	EnKF	EnOL	EnKF	EnOL	EnKF
1	4.16	3.84	5.63	4.02	7.00	6.99	8.37	5.40
2	5.34	4.91	6.66	5.96	6.36	5.73	10.78	8.14
3	3.62	3.06	5.04	4.35	5.96	4.85	10.64	8.13
4	3.79	3.65	4.41	3.55	5.83	5.03	9.00	7.56
5	9.72	8.30	6.89	5.49	8.43	7.83	6.06	5.03
6	6.19	5.19	5.47	5.26	7.56	6.31	5.25	4.29
7	8.30	6.75	7.48	6.99	6.45	5.88	7.36	6.82
8	8.76	6.59	6.63	4.96	5.21	5.2	5.71	4.67
9	5.95	5.38	5.16	5.09	7.33	6.43	5.43	3.91
10	8.95	7.64	6.44	5.66	8.92	8.54	7.62	6.21
11	6.03	5.10	6.21	4.89	9.88	8.32	11.43	8.30
12	7.17	6.37	7.33	7.42	6.24	5.01	6.58	5.95
13	6.25	5.34	6.80	5.91	7.90	7.55	8.84	8.53
14	12.67	10.16	11.43	9.01	9.34	7.97	9.29	7.21
15	8.83	8.28	10.28	10.08	9.78	8.31	10.08	9.89
16	12.74	9.58	13.20	10.60	9.76	8.32	10.44	9.78
17	12.01	9.17	11.10	9.54	7.59	6.14	7.90	6.38
18	7.23	7.50	8.62	7.94	9.59	8.42	9.51	7.88
Mean	7.65	6.49	7.49	6.48	7.73	6.82	8.35	6.89

Table A1. Names of the well locations used in this paper.

Location number	Name	Source
1	Sundern	Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen (http://www.elwasweb.nrw.de)
2	GEW KOELN 557	
3	SHELL GODORF GW I	
4	LGD BN-BEUEL	
5	Stetten S1	Bayerisches Landesamt für Umwelt (http://www.gkd.bayern.de)
6	Dietersdorf	
7	Haßfurt Q2	
8	Limbach Q1	
9	Rattelsdorf 136	
10	Faulbach	
11	01373X0130/A25	Portail national d'Accès aux Données sur les Eaux Souterraines (http://www.adès.eaufrance.fr)
12	02303X0065/P	
13	02307X0281/S	
14	01995X0030/563	
15	02344X0082/326E	
16	02344X0055/319	
17	02348X0009/319C (called A319C in this paper)	
18	03426X0197/136	

HESSD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



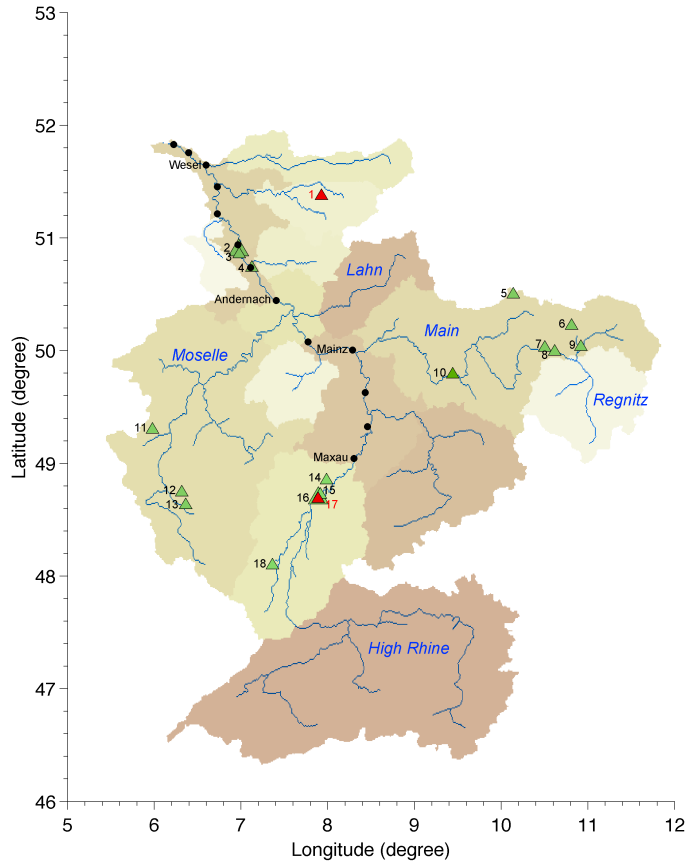


Figure 1. River gauge (circle) and well (triangle) locations over the Rhine River basin used in this paper. Red triangles indicate Sundern (1) and A319C locations (17). Names of all well locations are given in Table A1.

HESSD

11, 11837–11882, 2014

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

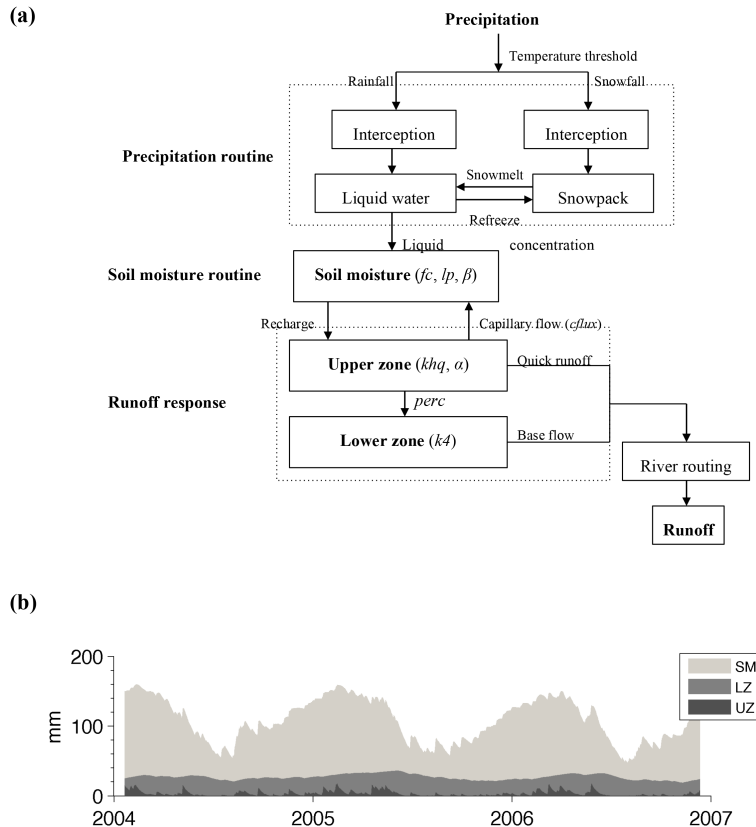


Figure 2. (a) OpenStreams-wflow model structure. (b) Sample results of the nominal run related to soil moisture (SM), lower zone (LZ), and upper zone (UZ) storages averaged over Rhine River basin.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

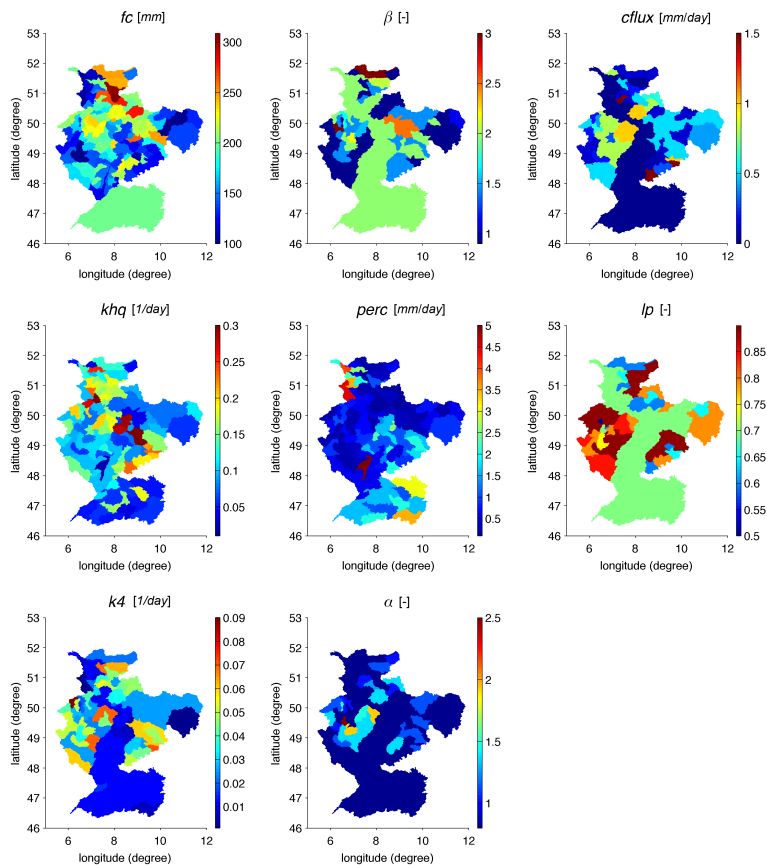


Figure 3. Calibrated parameters of the soil moisture and runoff response routines of the OpenStreams-wflow model.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

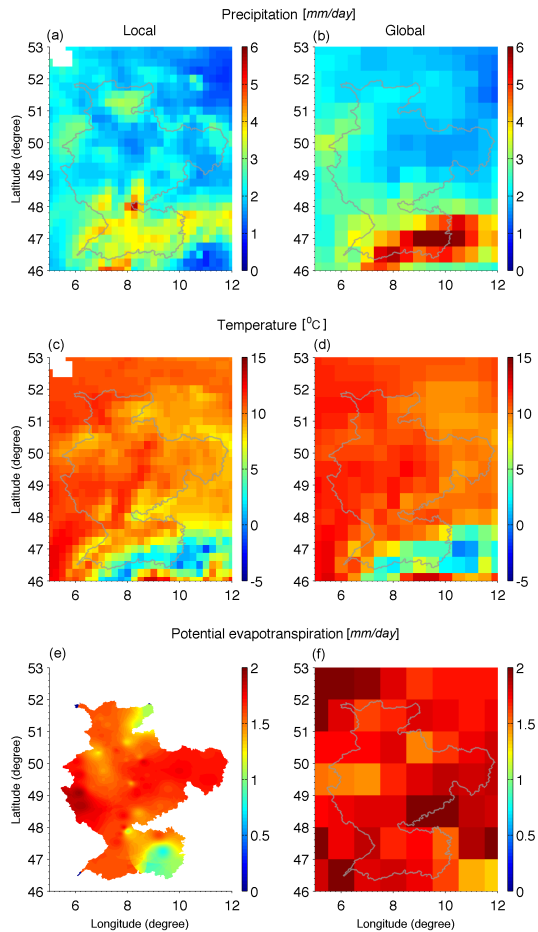


Figure 4. Mean daily precipitation, temperature, and potential evapotranspiration in 2006 from the local (left panels) and global (right panels) forcing datasets.

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

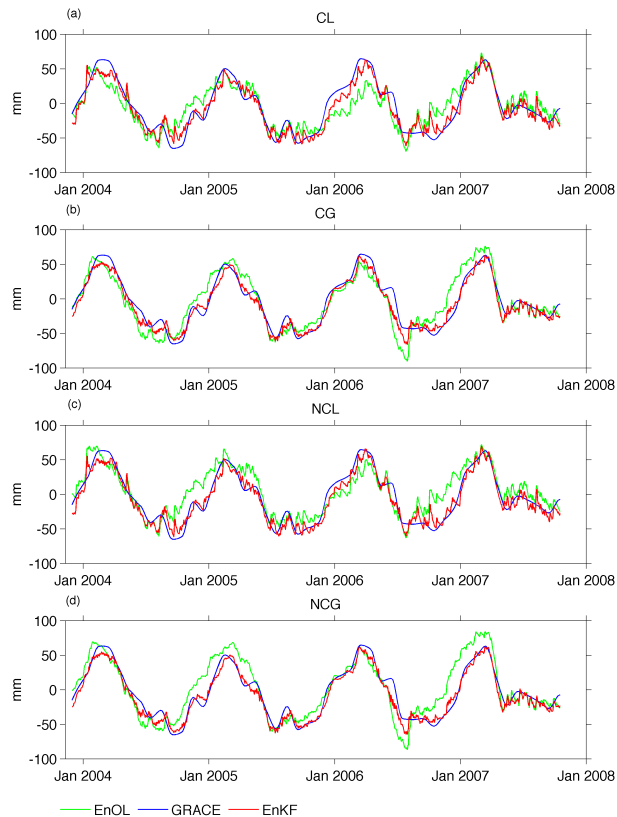


Figure 5. Area-averaged mean terrestrial water storage (TWS) over the Rhine River basin from the EnOL, EnKF and GRACE observations in 4 different scenarios (CL: calibrated parameters with local forcing data, CG: calibrated parameters with global forcing data, NCL: non-calibrated parameters with local forcing data, NCG: non-calibrated parameters with global forcing data).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

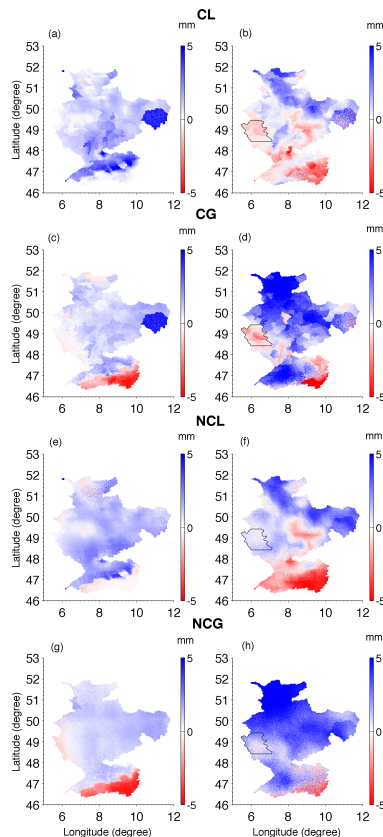


Figure 6. Averaged increment (posterior minus prior) of TWS in mm during the winter (left panels) and summer (right panels) of 2006 in 4 different scenarios (CL: calibrated parameters with local forcing data, CG: calibrated parameters with global forcing data, NCL: non-calibrated parameters with local forcing data, NCG: non-calibrated parameters with global forcing data). The polygons in the right column define the southern part of Moselle basin.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[⏪](#)
[⏩](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

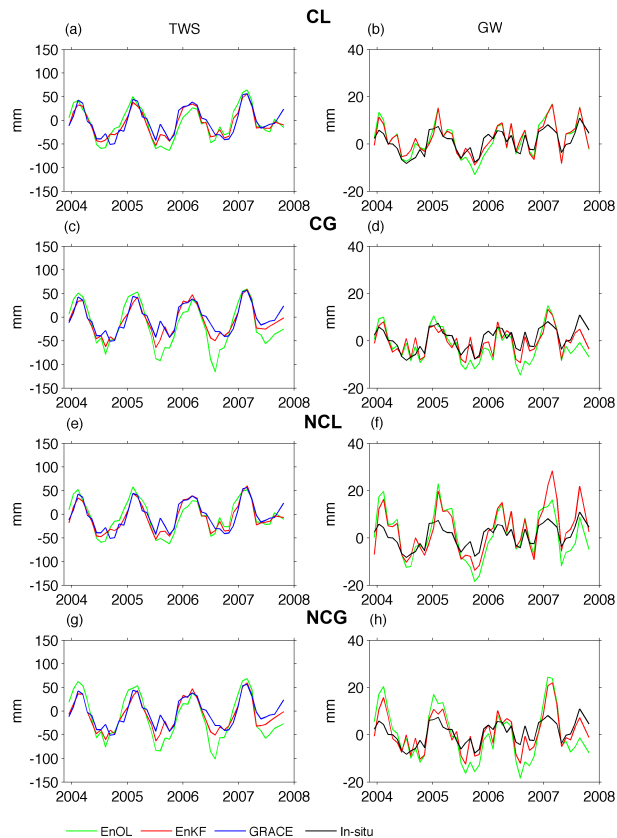


Figure 7. TWS variation (left panels) and GW variation (right panels) at the Sundern well location in 4 different scenarios (CL: calibrated parameters with local forcing data, CG: calibrated parameters with global forcing data, NCL: non-calibrated parameters with local forcing data, NCG: non-calibrated parameters with global forcing data).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

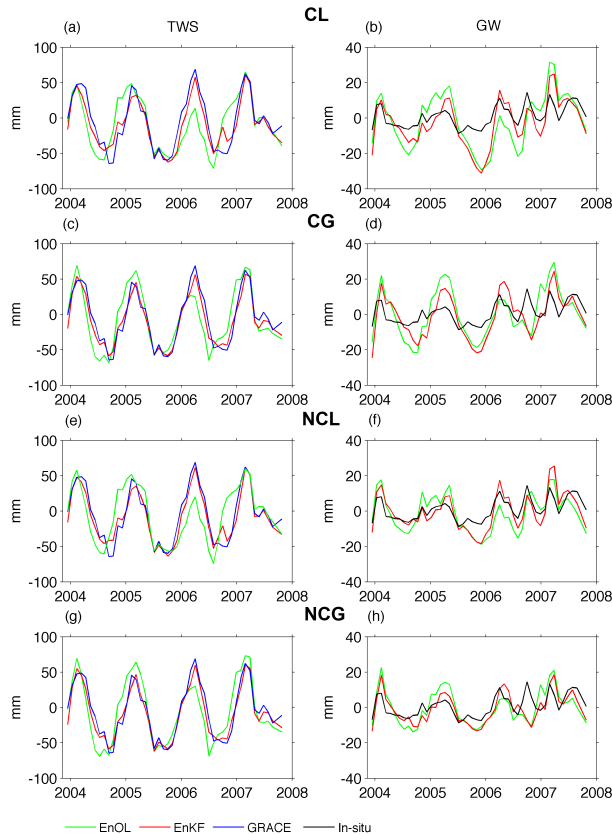


Figure 8. TWS variation (left panels) and GW variation (right panels) at the A319C well location in 4 different scenarios (CL: calibrated parameters with local forcing data, CG: calibrated parameters with global forcing data, NCL: non-calibrated parameters with local forcing data, NCG: non-calibrated parameters with global forcing data).

[Title Page](#)
[Abstract](#) [Introduction](#)
[Conclusions](#) [References](#)
[Tables](#) [Figures](#)
[◀](#) [▶](#)
[◀](#) [▶](#)
[Back](#) [Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)



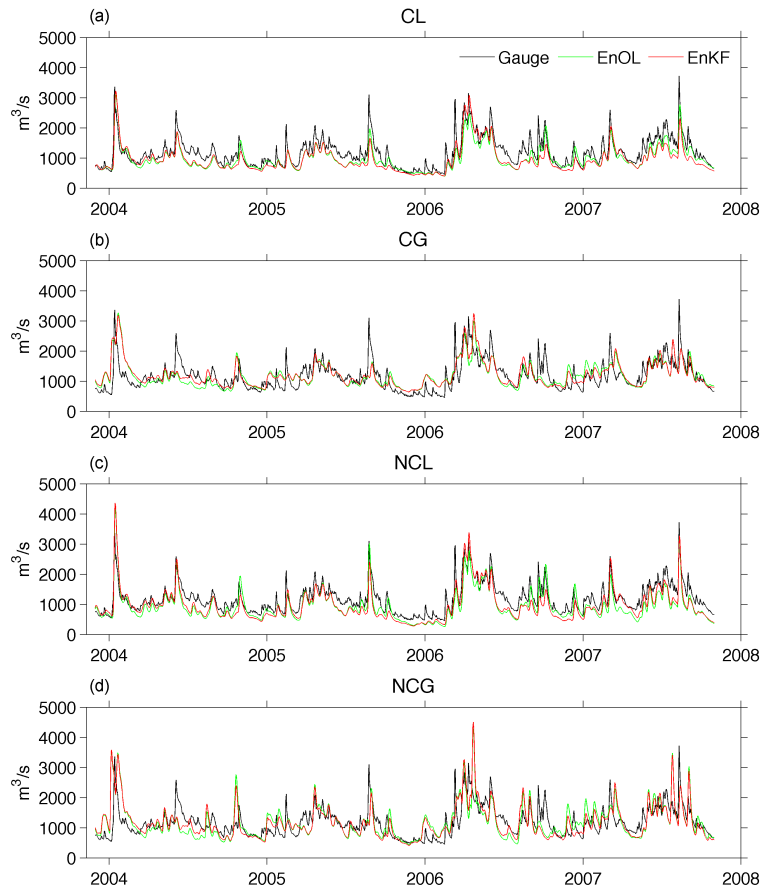


Figure 9. Estimated and observed streamflow at the Maxau gauge station in 4 different scenarios (CL: calibrated parameters with local forcing data, CG: calibrated parameters with global forcing data, NCL: non-calibrated parameters with local forcing data, NCG: non-calibrated parameters with global forcing data).

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
⏪	⏩
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



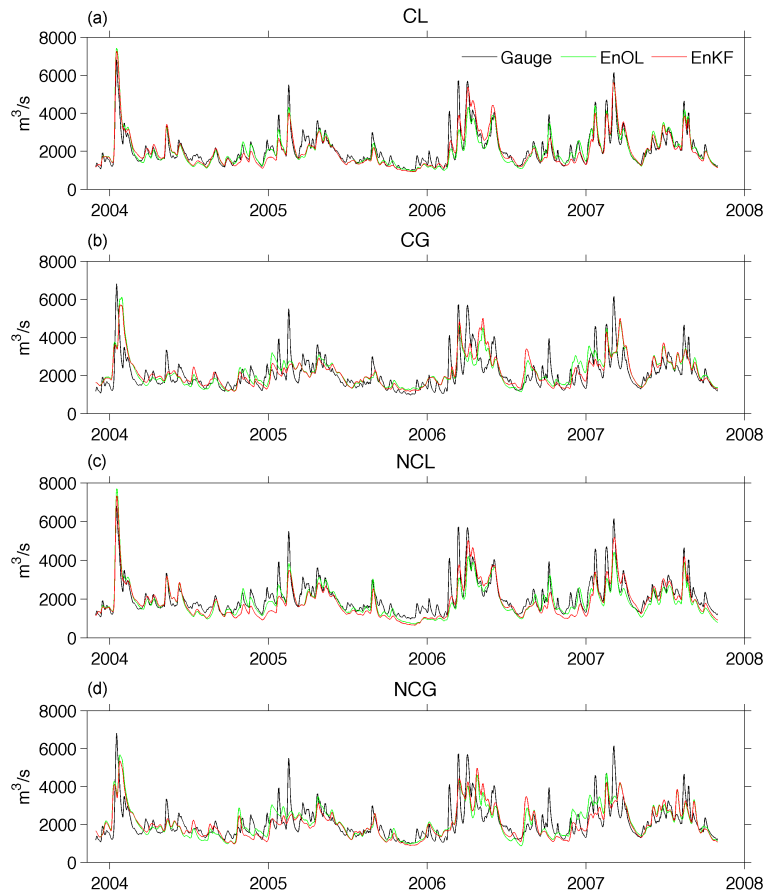


Figure 10. Estimated and observed streamflow at the Wesel gauge station in 4 different scenarios (CL: calibrated parameters with local forcing data, CG: calibrated parameters with global forcing data, NCL: non-calibrated parameters with local forcing data, NCG: non-calibrated parameters with global forcing data).

Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

[Title Page](#)
[Abstract](#) [Introduction](#)
[Conclusions](#) [References](#)
[Tables](#) [Figures](#)
⏪ ⏩
◀ ▶
[Back](#) [Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)



Data assimilation of GRACE terrestrial water storage estimates

N. Tangdamrongsub et al.

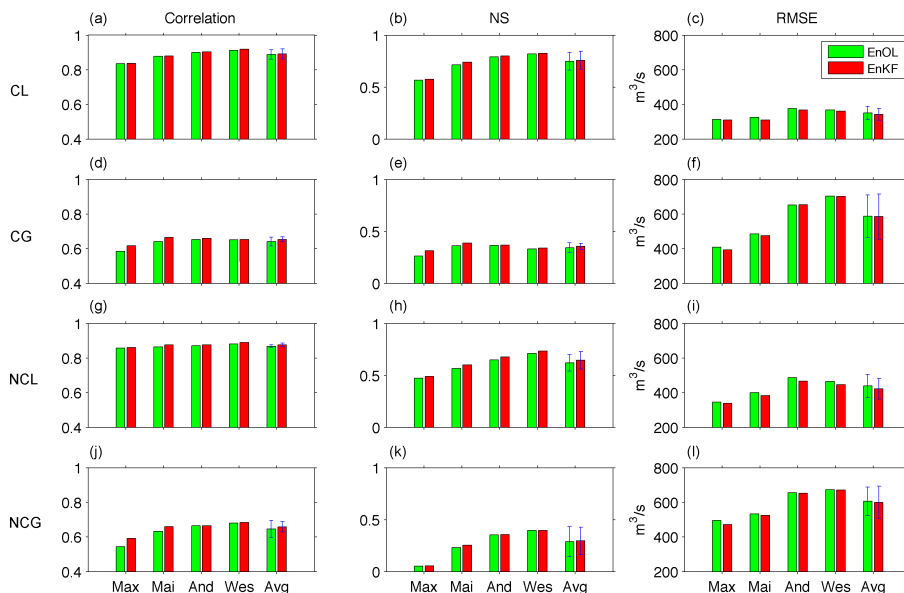


Figure 11. The correlation coefficient (left panels), Nash–Sutcliffe coefficient (middle panels) and RMS error (right panels) computed between estimated streamflows and gauge measurements in 4 different scenarios (CL: calibrated parameters with local forcing data, CG: calibrated parameters with global forcing data, NCL: non-calibrated parameters with local forcing data, NCG: non-calibrated parameters with global forcing data). Results are shown for the Maxau (Max), Mainz (Mai), Andernach (And), and Wesel (Wes) gauge stations. Average values (Avg) calculated across all gauge locations are shown in the rightmost bar of each histogram, with the SDs indicated by error bars.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

