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# Assessment of Gravity Recovery and Climate Experiment (GRACE) temporal signature over the upper Zambezi

H. C. Winsemius,[1] H. H. G. Savenije,[1] N. C. van de Giesen,[1] B. J. J. M. van den Hurk,[2]
E. A. Zapreeva,[3] and R. Klees[3]

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[1] The temporal signature of terrestrial storage changes inferred from the Gravity Recovery and Climate Experiment (GRACE) has been assessed by comparison with outputs from a calibrated hydrological model (lumped elementary watershed (LEW)) of the upper Zambezi and surroundings and an inspection of the within-month ground track coverage of GRACE together with spatial-temporal rainfall patterns. The comparison of the hydrological model with GRACE reveals temporal inconsistencies between both data sets. Because the LEW model has been calibrated and validated with independent data sources, we believe that this is a GRACE artifact. The within-month ground track coverage shows an irregular orbit behavior which may well cause aliasing in the GRACE monthly deconvolutions. This aliasing is the most probable cause of observed temporal inconsistencies between GRACE and other data sets.

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## 1. Introduction

[2] Various studies have compared terrestrial water storage data at river basin scale derived from the Gravity Recovery and Climate Experiment (GRACE) with other data sets. *Rodell et al.* [2004a] and *Andersen et al.* [2005] validated GRACE estimates of temporal variation in storage, in this article referred to as $\Delta S/\Delta t$, over the Mississippi and Europe, respectively. They compared them with estimates inferred from a combined atmospheric and terrestrial water balance using 40-year European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40) derived atmospheric moisture convergence [*Seneviratne et al.*, 2004], with soil moisture data from the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004b] and in situ gravimeter measurements. The comparison between these data sets generally shows agreement. However the temporal pattern is often not entirely comparable. Inconsistencies between GRACE and the other data sets in timing of the upgoing and downgoing storage can often be noticed. A possible reason may be that land surface models, such as GLDAS, only represents soil moisture in the unsaturated zone, while storage variation in groundwater and wetlands is not considered. GRACE, however, gives the total profile of water storage change in the Earth. *Andersen et al.* [2005] also left open the question whether the comparison of the coarse scale and spatially filtered solution of GRACE with ground observations at the point scale is valid.

[3] Apart from the aforementioned shortcomings in studies that try to validate GRACE with other data sets, we have concerns that the current monthly global solutions of GRACE spherical harmonics [*Tapley et al.*, 2004] may not be suitable for basin scale model enhancement. This is because GRACE orbits are irregularly spaced in time, which may regionally result in aliasing when the information collected during the orbits is weighed and averaged over both space and time. For instance during periods when the GRACE satellites are in an almost repeat orbit (e.g., in fall 2004), the intertrack spacing is relatively large, hence a target area is poorly sampled. This may cause loss of information about the temporal variability of both the true storage variation and the orbit behavior over, and in the neighborhood of, specific target areas. Naturally, such problems gain importance when the selected target area becomes smaller.

[4] The consideration of this possibility of aliasing is the subject of this study. It may be the cause of supposed temporal inconsistencies between the GRACE monthly spherical harmonic coefficients and other model results as could be noticed in the studies by *Rodell et al.* [2004a], *Andersen et al.* [2005], and more recently, J. W. Crowley et al. (Annual variations in water storage and precipitation in the Amazon basin: Bounding sink terms in the terrestrial hydrological balance using GRACE satellite gravity data, submitted to *Journal of Geodesy*, 2006). It also suggests that we could make better use of the GRACE overpass data by inferring a regionally specific storage estimate that is generated during periods when GRACE orbits are dense enough in the vicinity of the target area to provide a storage estimate. This would increase both the spatial and temporal

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[1] Department of Water Management, Delft University of Technology, Delft, Netherlands.

[2] Royal Netherlands Meteorological Institute, De Bilt, Netherlands.

[3] Department of Physical and Space Geodesy, Delft University of Technology, Delft, Netherlands.

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resolution of GRACE and would make the solutions more tailored to the target area. First results on a higher resolution in time and space have been obtained by *Schmidt et al.* [2006], *Rowlands et al.* [2005], and *Han et al.* [2005] over the Amazon.

[5] Another possible reason for the aforementioned temporal inconsistencies is the choice of a spatial filter radius. Application of a spatial filter is needed to reduce the noise due to hydrological signals that vary with a timescale shorter than one month, such as, for example, evaporation from intercepted water. Although the filter reduces these errors, it introduces new errors because part of the gravity anomaly of the target area leaks out of the target area and part of the outside anomaly leaks into the target area. This "leakage error" (described by, e.g., *Wahr et al.* [1998], *Swenson and Wahr* [2002], and *Swenson et al.* [2003]) thus may have a negative effect on the consistency of the GRACE time stamps, especially in an area governed by a large hydroclimatological gradient.

## 2. Methods

[6] To test both hypotheses, an independent regional storage estimate has been prepared over the upper Zambezi. It has been extracted from a regional hydrological model, covering the upper Zambezi and its surroundings. It has been used to show discrepancies in temporal consistency and resemblances with GRACE monthly spherical harmonic solutions. The upper Zambezi has been chosen because of the strong annual storage variation in this area, which resembles the occurrence of one yearly wet season and a long dry season. Moreover it has a large north-south oriented hydroclimatological gradient, which may result in large leakage errors when a spatial filter is applied.

[7] To ensure that all relevant stores are taken into account in the hydrological model, lateral redistribution of runoff in lakes and wetlands has been taken into account. Furthermore, to ensure that this model has a consistent behavior, its storage variation has been compared with storage variations from a combined atmospheric and terrestrial water balance, based on ERA-40 data. The emphasis was on the temporal consistency, in order to guarantee the temporal consistency of the hydrological model.

[8] Storage estimates from the hydrological model were filtered with the same filter as used for GRACE. Different filter radii of 600, 800 and 1000 km were applied on both data sets. GRACE has been compared with the hydrological model over the target area using these filter radii. The possible effect that these filters may have on the time stamp consistency has been assessed. Subsequently a qualitative analysis was performed on the possible aliasing in the GRACE monthly weighed solutions by assessing the within-month ground track coverage of GRACE over the target area, in combination with remotely sensed rainfall records.

## 3. Upper Zambezi

[9] The upper Zambezi is defined as the area upstream of Victoria Falls ($\sim$500,000 $(\mathrm{km})^2$). The river springs from the Kalene Hills in the northern areas of Zambia, flows to the west into Angola and shortly afterward bends southward entering the Western Province in Zambia. The climate of the Zambezi river basin is governed by the movement of the Intertropical Convergence Zone (ITCZ), which is responsible for the strong seasonal character of discharge in the Zambezi. Yearly rainfall amounts vary from about 500 mm $\mathrm{yr}^{-1}$ in the south to up to 1300 mm $\mathrm{yr}^{-1}$ in the north [*New et al.*, 2002]. Vast and shallow floodplains border the river, governed by very low slopes in elevation and high evaporation. The storage capacity of the large floodplains and wetlands, together with a very marked seasonality in rainfall, cause a large variation in storage over the year. Field observations in October 2005 showed that at the end of the dry season, at least 700 mm of water would be needed in these floodplains to raise the groundwater level to surface level. GRACE confirms that the area is subject to large storage variation over the year, which makes the Zambezi an excellent study area for exploring possibilities to use GRACE information to enhance hydrological models.

## 4. Data and Models

[10] The hydrological model was prepared according to the lumped elementary watershed (LEW) approach, which was introduced by *Winsemius et al.* [2006]. It covers the Zambezi, Congo, Okavango, Limpopo, parts of the Nile, Shebelle and smaller coastal river basins (Figure 1). The surroundings of the target area were incorporated to take into account the effects of leakage on filtered storage results. Unlike previous studies, we used a model that encompasses all terrestrial water stores: groundwater, soil moisture and wetlands. These are parameterized with simple bucket-like parsimonious model structures in order to avoid equifinality. A suitable parsimonious model structure was found by looking for a structure that on the one hand incorporated the hydrological processes that can be observed in the field and on the other hand showed identifiable parameters. This was done using the generalized likelihood uncertainty estimation (GLUE), described by *Beven and Binley* [1992] and *Beven and Freer* [2001]. Some model units represent lakes or wetlands, for instance the nearby lakes Kariba and Cahora Bassa, which have a unique model structure. Upstream routed runoff was redistributed over these model units to prevent artificial "losses" of water. The LEW model has been calibrated on monthly observed discharge records, of which the most were available within the upper Zambezi. The records are from several data sources. We may therefore state that the model performs quite good over the upper Zambezi.

[11] For the LEW model, two rainfall sources have been used: from 1978 until 2000, Climate Research Unit (CRU) data, based on observations, gridded to 0.5° resolution [*New et al.*, 2002]; between 2001 and 2006, the Famine Early Warning System daily accumulated rainfall estimates of 0.1° resolution (FEWS RFE 2.0) [*Herman et al.*, 1997]. These data have been aggregated to monthly values.

[12] The combined atmospheric and terrestrial water balance has been calculated and integrated into monthly time steps using the method described by *Seneviratne et al.* [2004]. Temporal variability in terrestrial water storage ($\Delta S/\Delta t$) over a river basin is computed by balancing terrestrial water storage variation with the moisture convergence integrated over the target area ($C$), regional moisture availability in the

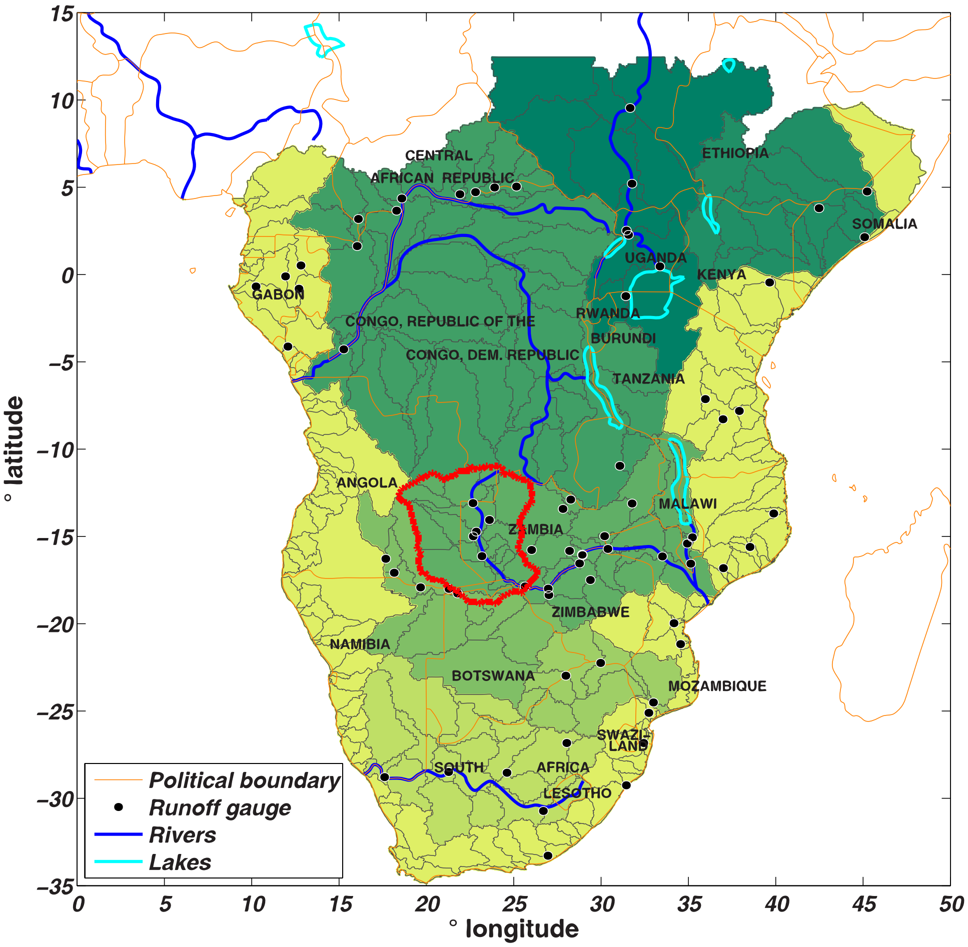


**Figure 1.** Model units derived for the upper Zambezi and its surroundings. The major river basins are displayed with a varying color scale from yellow to green. The upper Zambezi is given in red.

atmosphere ($W$), and river discharge ($Q$). It combines the following equations:

$$\frac{\Delta S}{\Delta t} = P - E - Q \tag{1}$$

$$\frac{\Delta W}{\Delta t} = C - (P - E) \tag{2}$$

$$\frac{\Delta S}{\Delta t} = C - \frac{\Delta W}{\Delta t} - Q \tag{3}$$

*Berbery and Rasmusson* [1999] defined a critical size for such a water balance computation of $5\ 10^5$ (km)$^2$, while *Yeh et al.* [1998] even suggest a critical size limit of $1\ 10^5$ (km)$^2$. Therefore we assume that the size of the upper Zambezi (ca. $5\ 10^5$ (km)$^2$) is above the critical size and is large enough to get at least an idea of the temporal pattern of storage.

[13] $W$ and $C$ are derived from ERA-40. The climate model fields used, have a resolution of 1.125°. $Q$ is measured in a runoff station near Victoria Falls, making $\Delta S/\Delta t$ the residual of this balance. The different fluxes presented above have been aggregated over the river basin area upstream of Victoria Falls. The truncation error in the lower levels caused by loss of horizontal detail due to the terrain following model coordinate system [*Trenberth*, 1995], is assumed to be small since the terrain of the upper Zambezi has small orographic variability. The resulting storage pattern from the LEW model has been compared with a time window of ERA-40 data from 1978 until 2002 (Figure 2). The temporal signature of $\Delta S/\Delta t$ from LEW agrees well with the signature of $\Delta S/\Delta t$ from the ERA-40 data. Particularly the correspondence between the LEW model and the convergence in the recent time series is good. The continuous state-updating increments and truncation errors in ERA-40 introduce an artificial source or sink, causing imbalances in the conservation of mass which accumulate in time. *Van den Hurk et al.* [2005] suggest that the imbalance can be accounted for by removing a moving average of the time series. The moving average declines in recent periods which may be the reason for a better resemblance between convergence and the LEW model in recent periods. The LEW model may also perform better in recent periods because it is driven by the less erroneous FEWS rainfall.

[14] Gravity field solutions from February 2003 until January 2006 were taken from GeoForschungsZentrum (GFZ) Potsdam's release 03. These data have been corrected

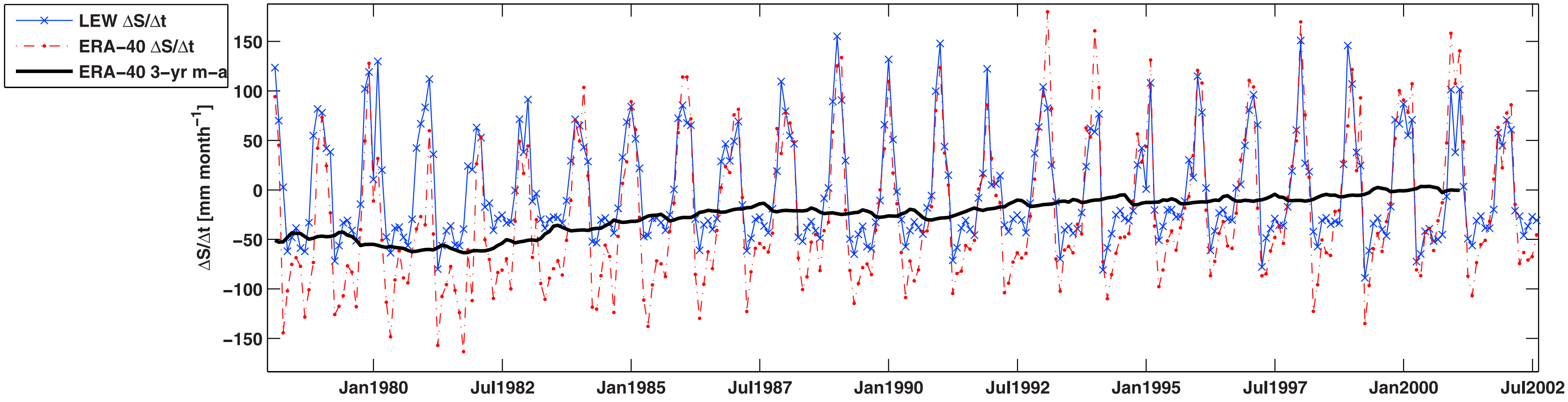


**Figure 2.** Convergence-derived estimates for $\Delta S/\Delta t$ versus LEW $\Delta S/\Delta t$. A 3-year moving average (m-a) of the convergence derived time series is also given. Time series covers a period between 1978 and 2002.

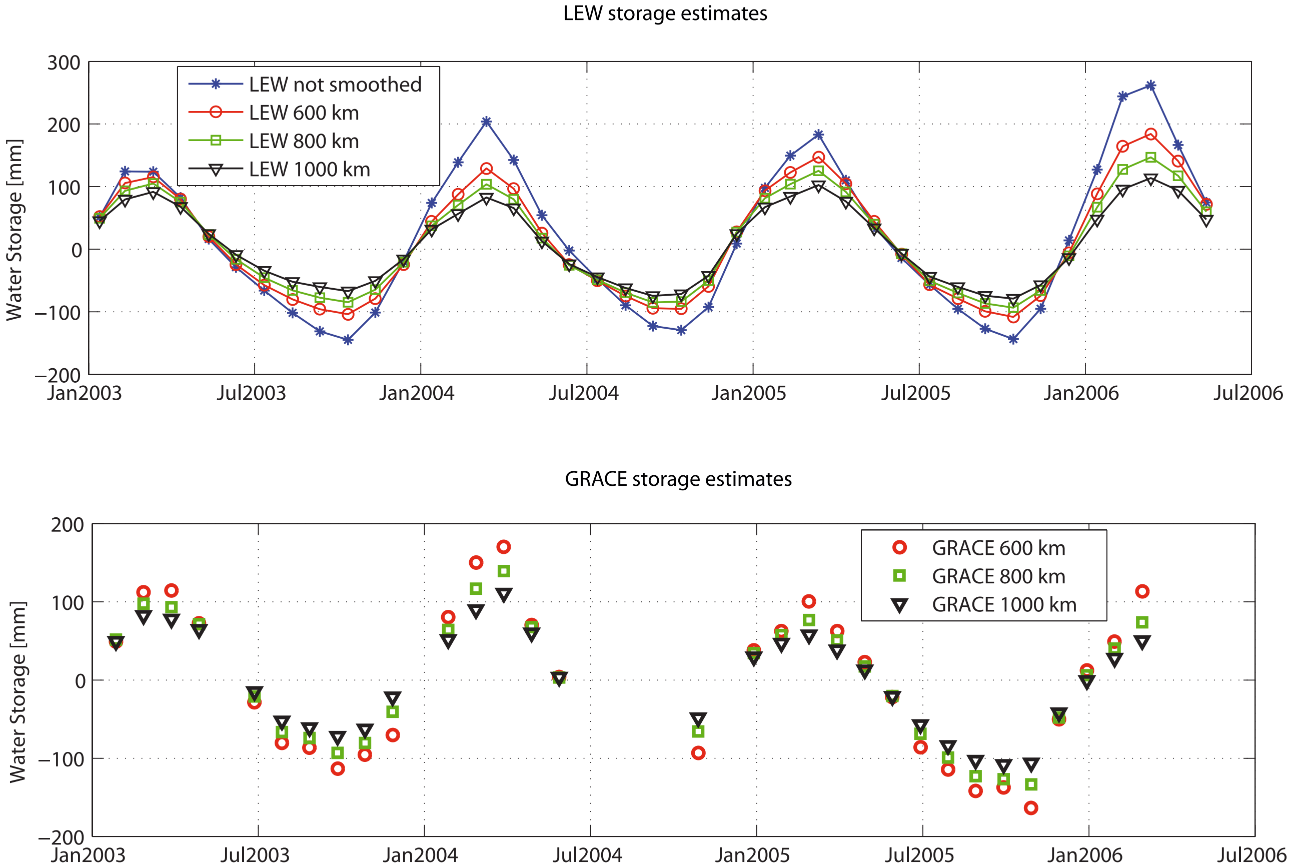


**Figure 3.** (top) LEW-inferred estimates of water storage with different spatial filter radii considered. The original modeled nonsmoothed estimate is also included. (Bottom) GRACE-inferred estimates of water storage with different spatial filter radii considered.

for oceanic and atmospheric contributions and converted to equivalent water storage heights.

## 5. Comparison of LEW and GRACE

[15] Gaussian-type filters with three different radii have been applied to both LEW model results and GRACE. Subsequently the area average storage estimates from both data sources over our target area have been compared. Figure 3 shows the effect of the filters on the LEW model results and GRACE. Comparisons of the filtered results demonstrate that the correlation coefficient of the data sets is insensitive to the chosen filter radius, reaching values of around 0.93 for all filters. In general, the resemblance is good. A filter with a large correlation length clearly reduces the level of information content. Figure 3 demonstrates that the filtering may slightly alter the apparent temporal signature of both data sets. This is because in some months the spatial variability in storage with respect to the surroundings of the target area may be larger than in other months. The filter then causes more spatial attenuation than when this variability is small. This can be

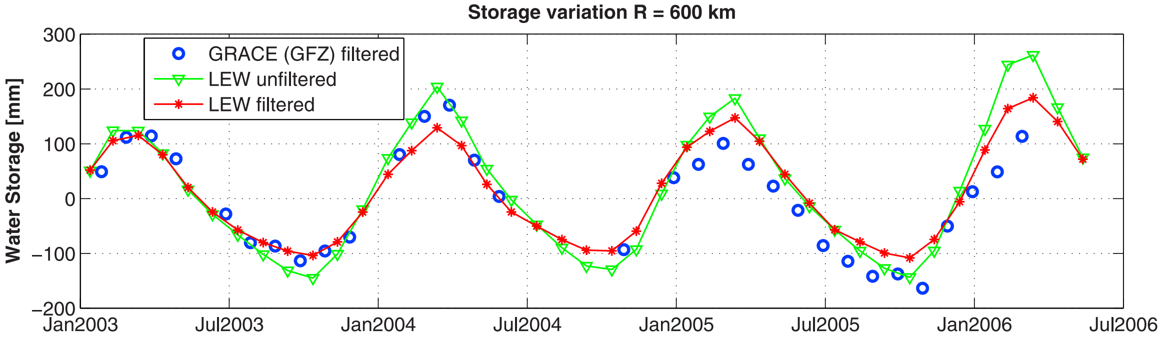
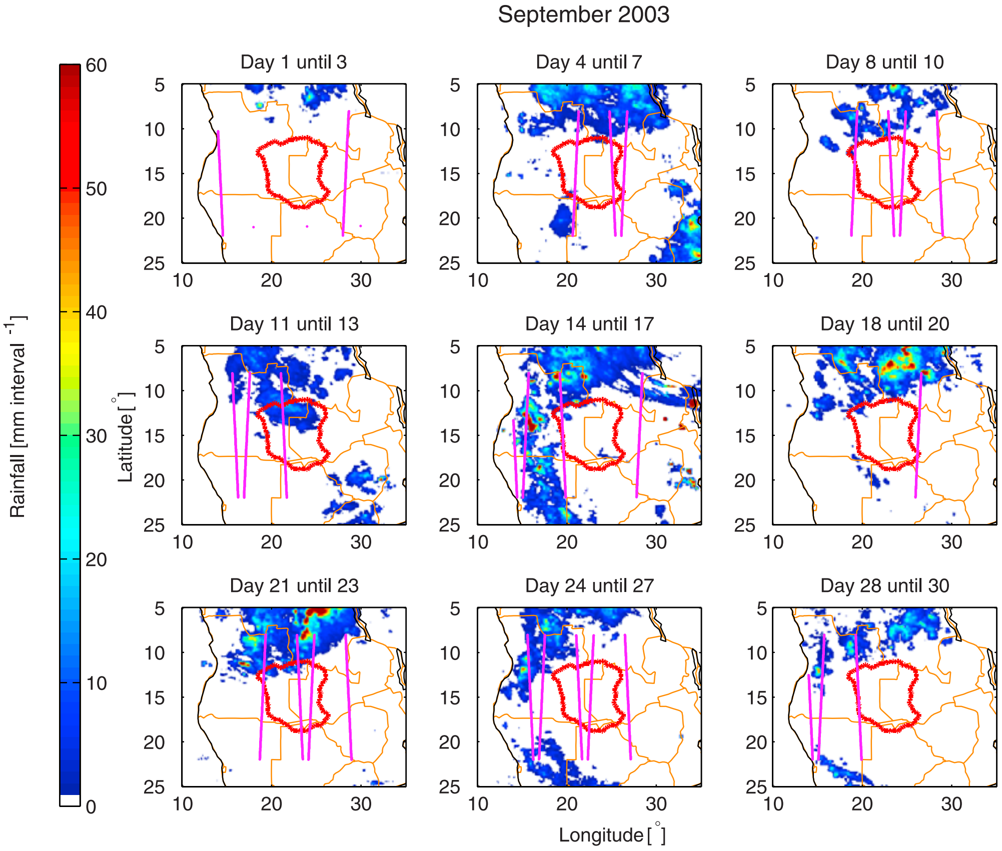


**Figure 4.** GRACE and LEW storage estimates, both derived with a Gaussian filter with a correlation length ($R$) of 600 km.


September 2003

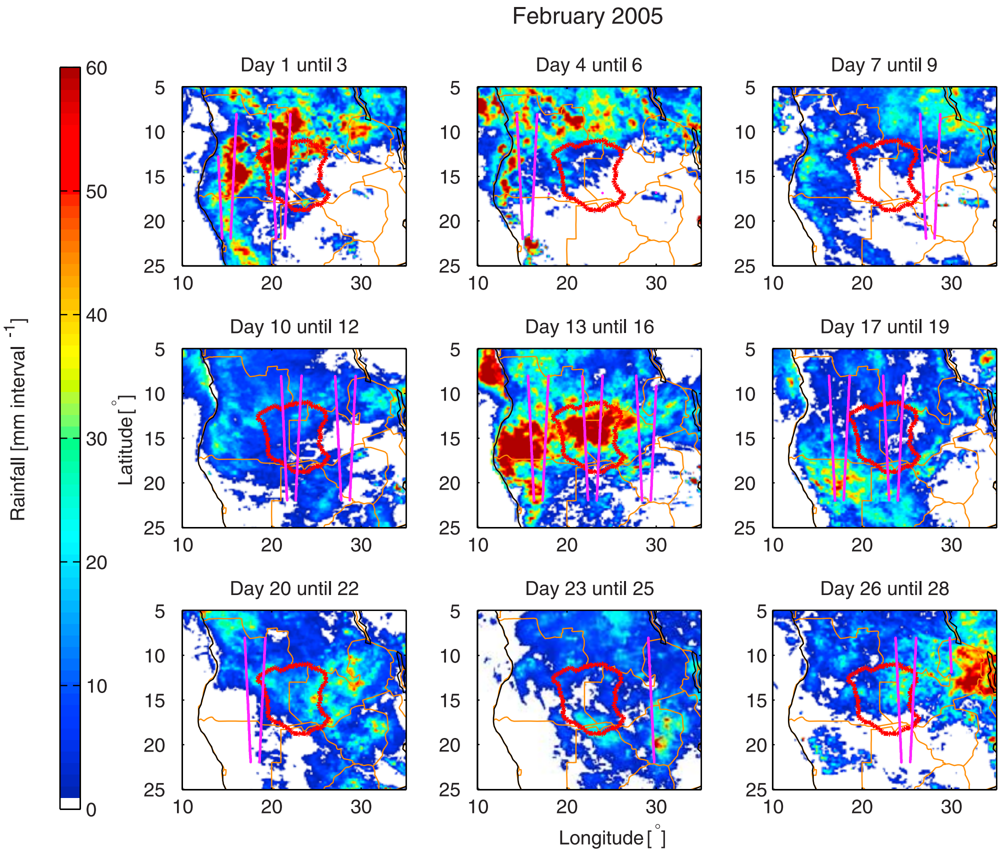

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**Figure 5.** (top) Ground track coverage during nine intervals of 3–4 days in September 2003. (bottom) Ground track coverage during nine intervals of 3–4 days in February 2005. The target area is delineated in red. Purple lines indicate the ground tracks.

observed best in the vicinity of the storage extremes. Between February and March 2003 for instance, the unfiltered LEW shows a slight decline in storage, while a slight increase may be observed in all filtered results. The GRACE time series in the same period however show exactly the opposite behavior, which may indicate that we are also dealing with effects from the already mentioned irregularity in the spacing of GRACE satellite orbits. A similar pattern can be observed between September and October 2004 in the LEW time series. During these months, the GRACE satellites moved along an almost repeat orbit and gravity field solutions had to be strongly regularized. Hence they do not provide reliable information about mass variations.

[16] In the remainder, we investigate discrepancies between GRACE and the LEW model in more detail. Figure 4 shows the combined GRACE and LEW results with a filter radius of 600 km. It seems as if a constant bias between the data sets appears in 2005, of which the reason is yet unresolved. Obvious discrepancies between the data sets can be observed in the months September 2003, where LEW shows a smooth decline while GRACE shows a slight irregularity, and February 2005, where LEW has a gradual storage increase, while GRACE shows irregular behavior. In October 2005 a similar pattern as in September 2003 can be observed in GRACE. These irregularities in Figure 4 will be further investigated in the next section.

## 6. Rainfall and Ground Tracks

[17] To illustrate how GRACE really samples our target area within one month and how this relates to within-month hydrological processes, we have investigated spatial and temporal rainfall patterns within a month in combination with ground track patterns. The FEWS RFE 2.0 rainfall maps mentioned in Section 4 have been used. Each observation period of approximately one month has been split up in 9 bins of about 3 or 4 days during which the ground tracks over the target area as well as the net rainfall ($P_n$) are jointly mapped. Net rainfall is defined as rainfall, exceeding a threshold of 2 mm day$^{-1}$ ($I$) to account for interception, the most dominating high-frequency hydrological process, according to the following equation [*Savenije*, 1997, 2004]:

$$P_n = \max(P - I, 0) \tag{4}$$

In this way, we try to visualize what the effect is of the spatial and temporal variability within a month of both the net rainfall and the GRACE orbit behavior on the final monthly GRACE solution. For this paper we have selected 2 months with obvious temporal inconsistencies between the LEW model and GRACE. For display purposes, we only show the ground tracks within the vicinity of about 500 km from the target area in the following results.

[18] Figure 5 (top) shows the GRACE observation period in September 2003. From the 9 displayed bins, we can already observe how irregularly spaced the ground tracks are. Evidently, September is close to the onset of the rainy season in this region and we can clearly see that hardly any rainfall is occurring within the target area. In the surroundings however, there is quite some rainfall and apparently GRACE picks up the consequent storage change which leaks into the solution for the upper Zambezi due to the limited spatial resolution of GRACE. It is not likely that this is merely a feature of the spatial filtering because then this inconsistency would also appear in the filtered LEW storage results. This type of error could be accounted for in a regional inversion by including prior information on the spatial-temporal correlation of mass variability, as can be observed from a large-scale model such as our LEW model.

[19] In February 2005, there is another clear inconsistency between the GRACE solutions and the LEW results. Figure 5 (bottom) illustrates the concurrent 3–4 daily ground track patterns within this month. First of all, most rainfall occurs within the first half of the month. There is quite a good GRACE sampling during these rainfall events. However, during the last half and especially the last week of February, GRACE does not cross the area in and around our target area very often, implying that there is only little sampling of our target area within this period. The combination of more rainfall in the beginning of the month and poor coverage in the end of the month suggests that for this month the weight of sampling and storage change is more toward the beginning of the month. Thus a time stamp shift toward the beginning of the month would have been more appropriate. This would yield a storage pattern, more consistent with our filtered hydrological model results. A proof of this shift would require a regional inversion of GRACE data, which has not been performed yet.

## 7. Conclusion and Discussion

[20] There appear to be temporal discrepancies between our hydrological model LEW and the GRACE models. *Swenson and Milly* [2006] suggest that discrepancies between atmospheric or hydrological models and GRACE observations may be due to erroneous precipitation amounts or suboptimal parameterization of river storage and seasonal inundation. However we have high confidence in the LEW temporal storage pattern. This is due to two reasons. First of all, we found an excellent match of the temporal storage pattern of LEW and ERA-40 data. This means that although ERA-40 data may be erroneous over Africa [*Trenberth et al.*, 2001] it still may have a consistent yearly pattern. Second, we have applied a regional hydrological model instead of a global model, which has been forced by observed rainfall. According to *Mohamed* [2005] the FEWS rainfall has no systematic bias and therefore it should follow the yearly rainfall patterns of the ITCZ. Buildup of biomass and delayed release of storage from nearby reservoirs are unlikely causes of discrepancies of this magnitude.

[21] Our main conclusion is therefore that the currently delivered monthly GRACE spherical harmonic coefficients may be aliased on the regional scale due to the fact that GRACE passes are irregularly spaced in time. By investigation of the within-month spatial-temporal ground track patterns together with rainfall estimates, we have shown that this is not necessarily a mere feature of spatial filtering. The irregularities observed are partly caused by the limited spatial resolution of GRACE, which causes aliasing of signal from outside the target area into the target area. However, it may also be caused by the irregular orbit spacing of the GRACE satellites. In some months, GRACE orbits the target area quite regularly while in other months the temporal weight of the orbits is clearly biased. This aliasing effect results in temporal inconsistencies between

GRACE and other data sets. Unfortunately, we can only give an indication that the monthly weighing procedure of GRACE deconvolutions may be inappropriate for regional applications. From the monthly gravity field solutions we are not able to deconvolute a more precise solution, tailored to regional target areas.

[22] To improve the spatial-temporal resolution of GRACE, regional deconvolution techniques using local basis functions (e.g., spherical radial basis functions or spherical wavelets) have to be applied instead of the commonly available monthly GRACE models. The solutions can be tailored on periods where GRACE provides a dense sampling of the target area (e.g., Figure 5 (bottom), days 13–16). Moreover, prior information about the spatial-temporal correlation of mass variations, which is available from our hydrological model, can be included in the regional deconvolution scheme, which further improves the spatial-temporal resolution of GRACE water storage estimates. Suitable algorithms for the regional inversion of GRACE data into mass variations are currently being developed and implemented. We hope the hydrological community will have access to these algorithms in order to enhance regional hydrological models with GRACE.

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R. Klees and E. A. Zapreeva, Department of Physical and Space Geodesy, Delft University of Technology, NL-2600 GA Delft, Netherlands.

H. H. G. Savenije, N. C. van de Giesen, and H. C. Winsemius, Department of Water Management, Delft University of Technology, P.O. Box 5048, NL-2600 GA Delft, Netherlands. (h.c.winsemius@tudelft.nl)

B. J. J. M. van den Hurk, Royal Netherlands Meteorological Institute, Postbus 201, NL-3730 AE De Bilt, Netherlands.