

***Interactive comment on* “The bias in GRACE estimates of continental water storage variations” by R. Klees et al.**

R. Klees et al.

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We are very pleased with the comments of the anonymous referee #4. They will help improve the clarity, completeness and quality of the paper.

1. The reviewer has identified some weakness in our approach:

1.1. we limit to a Gaussian filter;

1.2. we only use the LEW model to quantify the bias, which does not allow an independent assessment of GRACE or model uncertainties;

1.3. we need to use different hydrological models to assess model uncertainties and their influence on the bias;

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1.4. we assumed that the GRACE data quality is homogeneous throughout the 3 years but that the quality is quite inhomogeneous, which must reflect in the bias estimate.

Answer:

Ad 1: the bias depends on (i) the filter coefficients and (ii) the signal inside and outside the target area. Different filters and signals lead to different biases. We used the Gaussian filter, because this filter is the most often used filter in practical applications of GRACE so far. It is known that this filter is not optimal in whatever sense. However, to design an optimal (Wiener) filter, we need information about the signal and the noise; both are uncertain. When taking the uncertainty over signal and noise into account, it may happen that the Wiener filter does not perform better than any other filter. A study looking into the real performance of a Wiener filter compared to the more simple isotropic filters like the Gaussian is not known to the authors. There is a recent study by Sasgen et al. (2006), who claim that the Wiener optimal filter closely corresponds to a Gaussian filter provided that the correlation length of the Gaussian is properly chosen. Currently we investigate the design of optimal filters and how robust they are in terms of a priori information about signal and noise. But this is out of the scope of this paper. However, based on the results obtained so far, we do not expect that this changes the main conclusions of our study, namely (i) that the bias is significant and has to be taken into account, (ii) that in most practical circumstances, GRACE underestimates the amplitude of water storage variations, and (iii) that the a priori information available for most areas improves the quality of GRACE estimates significantly.

Ad 2: We used the LEW model, because we believe that this model provides us with estimates of the mass variation function in our target areas, which is at least as good as any global hydrological model. This is needed to obtain realistic order of magnitude estimates of the bias. First, it is not the scope of the paper to assess the quality of the LEW model or the quality of GRACE estimates. Second, a comment is given on the sole use of LEW as a priori knowledge to construct bias estimates due to leakage. It is not completely true that LEW has not been assessed with other information.

Winsemius et al. (2006) compared LEW with a quasi-independent estimation of the water storage over the Zambezi, based on a combined atmospheric-terrestrial water balance, using ERA-40 data of spatially integrated moisture convergence. It turns out that LEW is able to capture the yearly dynamics in water storage. This does not give us a clear estimation of its residual uncertainties but it does make this a completely independent validation of LEW, since no ERA-40 data whatsoever has been used as input for LEW. The uncertainty test, based on white noise disturbances of the rainfall input has been brought forward by the referee as being not enough to capture the true model uncertainty. This is indeed true, considering that there is uncertainty, not only in input data, but also in model structure and output data. Our main target here, was to get an idea of the effect of such uncertainties on the GRACE bias estimates, rather than exactly quantifying the effective uncertainty in LEW. The purpose of the LEW model is to obtain a priori information about the spatio-temporal distribution of storage variation, rather than the storage variation itself. The accuracy of the storage variation itself is therefore of less importance in the process of bias estimation. It is the spatio-temporal distribution of storage variation that causes the bias under investigation. Considering this, it is also likely that if a spatial filter with a radius in the order of magnitude of 1000 km is used, the spatial distribution of rainfall at the edges of the target area, may play a role in the bias estimates, which could also explain that there is not much inter-annual variation in the bias estimates when using the LDAS model. However this is somewhat a wild guess. With the assumption of a rainfall input error of 30% of the signal, we believe to obtain a rather pessimistic bias uncertainty estimate.

Ad 3: Other models, such as CPC-LDAS, are aimed at global modelling of the water cycle, in particular the feedback to the atmosphere, at a resolution, suitable for global circulation models. The input, used for CPC-LDAS is the 2.5 degree CPC Merged Analysis of Precipitation (CMAP), a completely different source than the FEWS rainfall records, that allow us to run and calibrate our regional LEW model on a much finer spatial scale (i.e. a subcatchment). Therefore, to use a comparison of two such completely different models, to assess model uncertainty (what the referee suggests) is

somewhat difficult. We assume that a white-noise Monte-carlo simulation is enough to capture the effect of the uncertainties of the LEW model on the bias estimates.

Ad 4: The quality of the GRACE models is not relevant here, because this information is not used to choose the correlation length of the Gaussian filter. Of course, if the filter is designed using information about the noise in GRACE monthly models (like a Wiener optimal filter), we would get a dependency of the bias on the quality of the GRACE models. To address this dependency, is out of the scope of this paper, but will be addressed in a forthcoming paper. The study by Sasgen et al. (2006) seems to indicate that the effect of the noise on the bias is small. However, more research is needed. Finally, also the signal-to-noise ratio will be important in this respect.

2. The reviewer criticizes that:

2.1. the bias correction method proposed has significant limitations, because we used only one target area, one hydrological model and one type of filter;

2.2. the conclusions are encouraging but not proved to be correct;

2.3. our conclusion about the necessity of a bias correction is wrong, because this problem is solved at the moment that aliasing, orbit characteristics, and accelerations are properly modeled in the GRACE data processing;

2.4. it cannot be the long-term solution to smooth GRACE data to make it useful.

Ad 1: It is difficult to agree with the reviewer, that the bias estimation method has some limitations caused by the considering of only certain region - Southern Africa. The methodology we used is applicable to any target area, any model of the signal, and any type of filter. We demonstrated the method on several spatial scales (four areas of different sizes) within a region where we do have a good quality information about the water storage variation and where the spatio-temporal variation of storage is large, because of the Inter-Tropical Convergence Zone. What depends on the target area, the mass variation function (which defines the signal) and the filter, is of course

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the magnitude of the bias. Studies by e.g. Velicogna and Wahr (2006), Chen et al. (2006b), Fenoglio-Marc et al. (2006), Sasgen et al. (2006), for other target area and filter functions, have proved that the bias is significant and that GRACE estimates need a significant re-scaling before they can be used. They also used a priori information about the mass variation function to obtain an estimate of the bias.

Ad 2: We have shown that after bias correction, GRACE fits significantly better to the output of the LEW model than without correction. There is one weak point in our computations, which has been addressed on Page 3574, I27+: we used LEW to estimate the bias and later-on compare LEW with bias-corrected GRACE to assess the performance of the bias correction. In that sense we could say that the estimated bias is "biased towards the LEW model" and therefore, the difference between LEW and bias-corrected GRACE is over-optimistic. That was the main motivation for us to compute the bias with another hydrological model, namely the CPC-LDAS model. This model is completely different from the LEW. Nevertheless, we could show that when the bias is estimated with this model, the fit between LEW and bias-corrected GRACE is much better than without bias correction.

Ad 3, 4: The situation since the launch of GRACE in 2002 is that spatial smoothing is necessary to obtain reasonable estimates of water storage variations from GRACE. Whether this will change in the future depends on alternative data processing strategies, among others regional inversion techniques with spatial-temporal covariance functions, which are being developed by various groups in the world. At the moment the spatial smoothing along the proposed by Swenson&Wahr (2006) "filtering - removal of the correlated errors" in GRACE data is a necessary procedure caused by the limited GRACE space resolution, configuration of the GRACE satellite formation and always being presented aliasing effects of residuals in atmosphere and ocean background models. Whether CSR at Texas University and GFZ in Potsdam will manage to improve the quality of the monthly GRACE models more than they have already done is an open issue for discussion. But it is clear that the new coming Release 04 (both

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GFZ and CSR) will not be so much different from the Release 03 (GFZ) or Release 01 (CSR) what indicates the importance and necessity of the application of the bias correction (personal communication with dr. B. Gunter (former CSR, PSG, TUDelft).

3. Discussion of our results in comparison with the ones by Crowley et al. (2006).

Some remarks can be given concerned the data used in the research described in the paper:

3.1. the data are different from ones we used: CSR GRACE gravity field models Release 01 used till maximum degree $l = 70$;

3.2. these data have quite a number of gaps and a very high GRACE noise for the period 2002-2003 that is why we do not consider them;

3.3. the GRACE CSR RL01 models differ from GFZ RL03 we used in our paper because of the different background models and the processing technique (GRACE GFZ/CSR L-2 Proc Standards Doc).

It is doubtful that the amplitudes for the Gaussian with correlation lengths 600 and 300 km can be so similar like they are in the paper by Crowley et al (2006)(Table 1.). It is not clear how they obtained such results for different filters. It is shown by many authors that the larger the correlation length the smaller the amplitude of the monthly mean water storage variation (e.g. Tamisiea et al., 2005; Chen et al., 2006a). Annual amplitude of the water storage variation averaged over the Congo area (3.9 mln. km²) for the 600 km Gaussian computed by Crowley et al (2006) is 30 mm while in our paper for the Congo+Zambezi area (5.2 mln. km²) it is about 48 mm. First of all the contribution of the water storage (WS) in the Zambezi river basin on the amplitude of the target area Congo+Zambezi is very large, the annual amplitude in the Zambezi is about 115 mm (4 times larger then in Congo). The size of the Zambezi basin constitute 1/4 of the target area Congo+Zambezi that is why our value for the annual amplitude is 1.5 times larger then from Crowley et al. (2006): If WS in the Congo area is about 30

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mm then the mean WS over Congo+Zambezi = $(30 \text{ mm} * 3 + 115 \text{ mm} * 1)/4 = 50 \text{ mm}$. Authors compare the water storage from GRACE with the precipitation data from CMAP and TRMM what gives them only a qualitative agreement (like seasonality effect) which is a well known fact. The quantitative analysis shows the large discrepancy (20-50 mm) between the estimates of the water storage variations from GRACE and precipitation from CMAP or TRMM data sets. It is still an ongoing process for the authors to get the final comparison of full water storage variation from GRACE and hydrology in-situ data, and for this we recommend them to correct their GRACE estimates for the bias. It is interesting to find the anticorrelation between Congo and Amazon river basin water storage variations inferred from GRACE what indeed can be a good subject for the future research.

4. There are some specific comments by the reviewer:

Page 3560, I15: we fully agree with the reviewer. Textual changes are not necessary.

Page 3562, I9: The LEW model is indeed considered as providing the "true" storage variation, when computing the bias. We will elaborate a bit more on this.

Page 3564, I20: We used the GRACE gravity field models up to the maximum degree 120 (GFZ RL03). So, there is no difference in the quality between monthly solutions. The reviewer probably references to the older models like GFZ RL01, RL02 and CSR RL01, where the maximum degree of the individual months varied between 70 and 150, but which are not involved into our computations.

Page 3566, I23: This is an important point. Of course, storage variation will change when other model structures are used. On monthly basis, we can consider the model structure as being a filter for the high frequency input, rainfall. Water is retained in the model structure and is released through impulse response functions, either in the form of evaporation or discharge. This causes retention of water and hysteresis effects between rainfall and outgoing fluxes. The model structure determines this hysteresis and response and therefore the storage behaviour. The monthly scale does not reveal

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high frequency responses, such as evaporation from interception and regional overland flow, meaning that these must be parameterized parsimoniously to prevent equifinality (see e.g. Beven & Freer., 2001). Suitable parsimonious model structures for the region of the Upper Zambezi (groundwater controlled areas with wetlands) have been studied by Winsemius et al. (2006) and have also been applied in this study. It could be an explanation for the fact that the bias correction underperforms when the whole Congo is also considered, because the model structure is simply not very compatible with the Congo's hydrology. Nonetheless, we have tried to regionalize the calibration process by using a nested discharge network. We will clarify the use of this model structure by referring more explicitly to this paper.

Page 3568, I18: The application of the LEW model in this paper is aimed at the bias correction. To estimate this bias, a rough estimation in general should be enough, because we are not specifically interested in the accurateness of the storage variation as such, but more in the spatial distribution of this variation. This will also be clarified in this section. The fact that after bias correction, GRACE and LEW compare quite well is a proof that the bias correction is effective.

Page 3568, I25: We will clarify this.

Page 3570, I8: This is an important point. We followed the standard procedure, because simply restoring of these coefficients from other satellite data is not uncritical. The proper solution is to consider the coefficients provided by other types of satellite data as stochastic a priori information in the estimation of the GRACE monthly gravity field models. This is not done by CSR and GFZ. In some recent studies (e.g. Chen et al. 2004, 2005 and Fenoglio-Marc et al., 2006) the degree 1 terms and the degree 2 zonal term have been restored from SLR data to obtain the full mass variation signal. Chen et al. (2004, 2005) concluded that the substituting SLR and EOP estimates of degree 2 coefficients generally improves the agreement of the estimated water storage variations from GRACE with a hydrological model output, but it strongly depends on the location, size and the water storage variation in the target area. Thus we made

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some calculations of the contribution of all degree 1 and zonal degree 2 coefficients to the bias estimates. Degree 1 coefficients have been computed by using geocenter motions parameters: annual and semiannual amplitudes, and phases given in Table 1 by Chen et al. (1999) and the equation (16) by Kusche & Schrama (2005). The results show that the influence of the included degree 1 coefficients on the bias estimates is between 2% (for Upper Zambezi) and 5% (for Zambezi+Congo). To get an idea about the influence of the included C20 from both GRACE and SLR we:

1. included GFZ RL03 degree 2 zonal term. At the moment it is advised to include C20 from GFZ RL03 solution or upcoming CSR/GFZ RL04 solutions (personal communication with dr. F. Fletchner (GFZ) and dr. B. Gunter (TUDelft));
2. computed time variation of C20 using annual amplitudes and phases from SLR solutions given in Table 1 by Nerem et al. (2000).

We found that the degree 2 zonal term can contribute to the water storage variation averaged over the target area from the bias-corrected GRACE solution up to 10-15% depending on the area. SLR data give better estimates of the C20 and less influence on the bias estimates and consequently on the water storage what has been also observed by Fenoglio-Marc et al. (2006). The total effect of the both degree 1 and degree 2 zonal term coefficients is proved to be at the level 5-10%, what shows the partial cancelation of the separate effects.

Page 3570, I14: As mentioned, the LEW model runs on monthly time steps. Therefore it is not possible to evaluate it at precisely the time stamp of the GRACE model.

Page 3570, I28: The current formulation is a bit misleading and we will clarify this. Differences between bias-corrected GRACE and LEW model output are caused by (i) errors in the bias-corrected GRACE estimates and (ii) uncertainties in the LEW model output. Currently, we are not able to separate the two error sources. Moreover, since LEW model output is also used to compute the bias, uncertainties in the LEW model output will also contribute to the errors in the bias-corrected GRACE estimates. The

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point we wanted to make is why monthly differences are larger than yearly differences. A possible explanation has been given on Page 3574, I6-I13.

Page 3571, I21 (the reviewer referred to it as Page 3572, I21): Here, we simply want to comment on a large difference for one particular period between bias-corrected GRACE and LEW. It is the only period within the 3-year time span considered in this study, where after bias correction the difference between GRACE and LEW is still significant.

Page 3571, I26 (the reviewer referred to it as Page 2572, I26): The reviewer addresses an important point. This has to be taken into account when designing a Wiener optimal filter. As already mentioned before, this is out of the scope of this paper.

Page 3572, I24+: The Monte-Carlo analysis was used to give an indication of the impact of such uncertainties on the resulting bias correction, but was not meant to give the "true" uncertainties. We will describe the purpose of these simulations in more detail.

5. Technical comments by the reviewer:

Page 3582: will be corrected for.

6. References:

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