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Hydrology and Earth System Sciences
Discussions

# *Interactive comment on* "Daily GRACE gravity field solutions track major flood events in the Ganges-Brahmaputra Delta" *by* Ben T. Gouweleeuw et al.

**Ben T. Gouweleeuw et al.**

bingo@gfz-potsdam.de

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1. (P2,L14). Delivery of GRACE L1 takes 11 days as mentioned in introduction. How is it possible to produce the daily solution in 5 days? Do you have another improvement for the L1 data processing?

Authors' reply: The authors suggest to add the following sentence to the text in the manuscript (P2, L4): "Additionally, quick-look Level-1 data with a time delay of 1 day are made available on request by NASA Jet Propulsion Laboratory (JPL)."

2. (P3,Eq(3-4)). Please explain explicitly about k and N.



Authors' reply: The authors thank the reviewer for this observation and have phrased a reply also with reference to comment 3 of the second reviewer (see below). As the methodology of the derivation of the empirical covariance matrices is presented in detail in Kurtenbach et al., 2012, the equations in Section 2 have been removed from the text. We suggest to adapt the manuscript to as follows:

"Compared to monthly solutions, the limited spatial coverage within one day does not allow for GRACE to observe the full gravity field signal alone. Limited spatial sampling in East-West direction means that GRACE contributes little to no information to potential coefficients with orders higher than approximately 15. It is therefore necessary to introduce additional information to obtain reliable estimates of the full global gravity field signal. Applied to the determination of daily gravity field variations, this means that information on how the variable gravity field evolves with time is required. Since geophysical processes are not random, one can assume that the Earth's time-variable gravity field does not change arbitrarily from one day to the next. Kurtenbach et al., (2012) proposed to model this temporal evolution as a first-order Markov process, which can be fully described by its auto- and cross-covariance. Applied to daily GRACE solutions, the process to be modelled is the residual gravity field signal that is present in the observations after other effects, such as long-term, secular, as well as non-tidal ocean and atmosphere variations have been reduced. The main geophysical constituents left in the GRACE data are therefore continental hydrology, cryosphere, solid earth and errors in the background models (Kurtenbach et al., 2012). For the daily solutions of the ITSG-Grace2014 release (Mayer-Gürr et al., 2014) used in this analysis, the model output of the updated ESA Earth System Model (Dobslaw et al., 2015) is used to approximate the unknown covariance structure of this residual gravity field signal. The 6-hourly model output is resampled to one day using daily averaging. These daily averages are subsequently reduced by their sample mean, trend and annual signal. Finally, the empirical auto- and cross-covariance is computed from the resulting state vectors."

3. (3.1 Process dynamics). I understood that two daily solutions differ mostly from realization of matrix B that is empirically estimated by models. And, Figure 1 shows that solutions are close to each other regardless of models for B. Why don't you present the variance and co-variance matrix first?

Authors' reply: The gravity field solutions of GFZ and TUG do also differ significantly in how the GRACE data is processed. Figure 1 highlights the fact that the process dynamic itself does not greatly affect the solution – which means that the major part of the differences stem from the underlying GRACE processing strategies.

4. (P5,L4-9). Why the sampling dates of daily solutions are not the same? Is this due to noise so that some daily solutions could not present such nice snapshots? Indeed, GFZ RBF is corrupted more noise as shown in Figures 4 and 9.

Authors' reply: In part due to the different process dynamics of the daily gravity solutions causing different levels of noise, as pointed out by the reviewer, these peaks fall on different dates. This is -to some degree- indicated on the same page (P5, L30) with regard to the run off peak on 23 July 2004, which is reflected in HPF water storage signals of ITSG-Grace2014 and GFZ RBF on 21 and 24 July, respectively. Similarly, for the 2007 flood on P6, L21-22 it is offered: "As in 2004, the two daily solutions do not necessarily peak on the same day". The authors agree, however, the rational for the choice of sampling dates should be made more sufficiently clear. Therefore, the following line is suggested to be added to the text in the manuscript: "The sampling dates are chosen such that they represent the (local) peaks in the respective (high-pass filtered (HPF)) daily gravity time series corresponding with discharge peaks."

5. (P5, L9 "Due to the different. . ."). However, monthly mean of daily solutions need to be compared with monthly solutions. This is important because you examined the LPF of daily solutions. In terms of month-to-month variation, monthly solutions should be superior to monthly mean of daily solutions.

Authors' reply: The authors thank the reviewer for this suggestion, which we consider



correct. The focus of the paper, however, is on the added value of an increased temporal resolution of changes in the gravity field, i.e., the daily solutions, in terms of monitoring (extreme) hydrological events/floods. One could argue the increased capacity to monitor these events with a higher temporal resolution comes at the cost of signal accuracy, due to the Kalman filter.

6. (P5, L30) Correlation coefficients, r, in Table 1 are based on entire flooding years (am I right?). But you talked about r during flooding epochs in the text. I was quite confused during reading this part. So, please be clear this. It seems that many r in the table is not meaningful in the text. You may include r during flooding events in the table. Furthermore, r during flooding events are statistically significant? What are p values? (The 2007 flood) Similar comments for 'the 2004 flood' are also applied here.

Authors' reply: The authors thank the reviewer for pointing this out. The correlation coefficients (r) in Table 1 for the entire flooding years are contrasted with shorter (flooding) periods in the text, which exhibit higher correlation for shorter periods during which water storage peaks, as reflected in the LPF signal. Correlation coefficients during flooding are equally significant to those for the entire flooding year ($p < 0.01$), which are added to the text. To avoid confusion for the reader r for the entire flooding year and for the shorter flooding period is separated in Table and text in the revised manuscript.

7. (P7, L18) "..added value of the daily GRACE..") Did you mean ".. the monthly GRACE.."?

Authors' reply: In terms of short-term variations, the daily solutions do provide added value.

8. (Figure 10). Explanation for Figure 10 is quite terse. More explanations would be necessary for GRACE audience.

Authors' reply: Following the reviewer's comment, the text has been adjusted as follows: "This is further illustrated in Figure 10, which shows the frequency-separated anomalies of river runoff vs. total water storage in the GBD for the flood years of 2004 and 2007 (Riegger and Tourian, 2014; Reager et al., 2015; Sproles et al., 2015). Generally, the hypothesis that storage can drive river runoff tends to indicate a slower process evolution through subsurface water storage and base flow generation, expressed by a strong correlation at longer (monthly) time scales. Daily HPF runoff is expected to be less correlated with and more variable than daily HPF storage, caused by precipitation than runs off quickly and doesn't enter storage for a significant amount of time. The fact that there is still a strong correlation between daily HPF storage and HPF river runoff, particularly for the 2007 flood (Table 1), points towards a scenario of increased storage in the river itself, in which the variation of daily total water storage reflects the inflow of river water into the delta. This water inflow can only be stored in the river during the time of flooding, when the available water storage in the area is at (near) capacity. However, while trends of the HPF signal of daily water storage and river runoff anomalies show agreement over periods of a few days, the higher frequency content of the daily solutions is not reflected in the daily river runoff. This high-frequency variation is attributed to process noise of the Kalman filter approach and a repeat period of 4 days for GRACE to pass over the GBD. Propagation of the full formal error matrix to the area mean value for each time step estimates the resulting noise level in the ITSG-Grace2014 and GFZ RBF daily solutions at approximately 1 cm TWSA and 1.45 cm TWSA, respectively. These numbers are confirmed by an empirical estimate using the methodology of Bonin et al. (2012). The difference in apparent noise in the two daily time series can primarily be attributed to the process models employed, which result in different temporal constraints and degree of spatial filtering."

9. (Figures 4 and 9) Both LPF time series quite differ from each other. This is not consistent with results in Figure 1.

Authors' reply: The gravity field solutions of GFZ and TUG also differ significantly in the way how the GRACE data is processed. Figure 1 highlights the fact that the process dynamics itself does not greatly affect the solution – which means that the major part



of the differences stem from the underlying GRACE processing strategies.

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