Hydrol. Earth Syst. Sci. Discuss.,
doi:10.5194/hess-2016-354-AC1, 2016


Hydrology and Earth System Sciences
Open Access
Discussions

# *Interactive comment on* "Improving estimates of water resources in a semi-arid region by assimilating GRACE data into the PCR-GLOBWB hydrological model" *by* N. Tangdamrongsub et al.

**N. Tangdamrongsub et al.**

natthachet.tangdamrongsub@newcastle.edu.au

Received and published: 9 November 2016

We firstly would like to acknowledge the insightful comments and suggestions provided by Dr. Bogena. Followings are the responses (R) based on the comments:

General comments concerning the hydrological modelling:

The interactive modules for simulating water abstraction etc. with the PCR-GLOBWB model are described in greater detail, but these did not be used in this study. Thus the model description should focus on the considered process.

R1: We agree with reviewer and the model description will be modified to be more concise in the revised manuscript.



The model parameterisation with respect to the soil hydraulic properties needs to be better described.

R2: More description of the soil properties will be added to the revised manuscript (please also see R40).

I suggest adding some plots showing the special distribution of simulated TWS for the different DA scenarios.

R3: An illustration of the spatial distribution of both DA scenarios will be shown in Fig. 11 in the revised manuscript. The following discussion will also be added in the revised manuscript: "It is also worth discussing the impact of GRACE DA on the spatial pattern of the water storage estimates. To demonstrate this, the update term ($\Delta$A in Eq. (7)) of October 2002 from EnKF 1D and 3D cases is shown in Fig. 11. Only TWSV, SMSV, and GWSV are shown, since other components (snow, surface water, and interception) are small. As discussed above, EnKF 3D shows smaller update in all components. Due to a greater amplitude of GRACE-derived TWSV over northern and southern parts of the region (see Fig. 4), the update is mostly seen there. Almost all update is limited to the soil moisture layer. Higher precipitation is generally observed over the southern part, which leads to higher groundwater recharge (and GWSV) over that region. As such, GWSV update is clearly seen over the southern part of the region."

In the DA scheme only TWS is considered. It is no clear, how "added" or "subtracted" water was distributed by DA to the different model storages (e.g. SM, GW, snow).

R4: As only TWSV is available from GRACE, TWSV is only used in the discussion in Sect. 6.1. However, the discussion of GRACE DA impact on individual stores are given Sect. 6.2 of the revised manuscript.

Compared to the model results the variations in GRACE determined TWS are much more pronounced. Possible reasons should be discussed in greater (e.g. influence of the pattern restauration procedure).

R5: This discussion will be added to the revised manuscript as follows: "It is seen that GRACE-derived TWSV is more pronounced compared to the model estimated TWSV. This can likely be attributed to the poor quality of the model parameter calibration and the accuracy of the meteorological input data over the data-sparse regions. In the absence of observations, model parameters are difficult to determine and only the best available knowledge (or guess) is generally used, leading to inaccurate model state estimates. Updating the water storage estimates using GRACE DA showed a clear improvement in this condition."

It is unclear if at all or how groundwater abstraction was considered in the modelling. If this was considered, why was the groundwater abstraction not considered in the DA (e.g. by updating the groundwater abstraction parameter)?

R6: In this study, the state vector only contains the water storage. Groundwater abstraction is one of PCR-GLOBWB's model parameters, and it is not included in the state vector. Therefore, the groundwater abstraction is not updated or separately estimated in this study, but it is treated. Please also see R45 for more detail.

Specific comments

Title: The term "semi-arid" is not correct (see below)

R7: The "semi-arid" term is used based on Zhu et al. (2015). Please see also R10.

At times TWS variations are simply termed "TWS". This is somewhat confusing. The terms "TWS variations" or short "TWSV" should be always used.

R8: TWS variation will be changed to TWSV in the revised manuscript. Similarly, soil moisture storage variation and groundwater storage variation will be abbreviated as SMSV and GWSV.

L45: The groundwater well data should integrate of smaller areas than the catchment area of the streamflow data. Therefore, I am not convinced that this is a problem of spatial resolution.



R9: Reviewer statement is correct over a sufficiently large river basin. As GRACE spatial resolution is ~250 km or larger, the TWSV signal of the smaller basin can be easily interfered by the neighbouring basin. This is known as a leakage effect and such an effect is seen over the Hexi Corridor. Therefore, the limited spatial resolution of GRACE plays a very important role on the state estimates there.

L57-59: According to the Köppen climate classification this region belongs to "cold desert climate" (BWk).

R10: The "semi-arid" term is used based on Zhu et al. (2015); however, we also realize that much of the region has a cold desert climate, and this can be found in the submitted manuscript (line 152): "Located next to the Gobi Desert, most parts of the region have a cold desert climate, . . ." For clarity, we will include the references of both climate classifications (Zhu et al. (2015) and Peel et al. (2007)) in section 2 of the revised manuscript.

L67-68: This depends largely on the measured variable. For instance, streamwater discharge data provides integrated information for large catchment areas.

R11: We agree with reviewer. In the revised manuscript, this sentence will be written as follows: "While streamflow gauges provide an integrated information for large catchment areas, point observations of hydrometeorological variables and even groundwater levels can be very local in scope."

L81: In addition, hydrological models typically suffer from inadequate process representations (model structure errors).

R12: The suggested statement will be added to the introduction section of the revised manuscript.

L98: "jump" of what?

R13: "jump" will be extended to "jump of the water storage estimates" in the revised manuscript.

L115: What is the size of the area?

R14: The size of the individual basin varies between 41,600 and 157,000 km2. This can be found in lines 149 - 151 of the submitted manuscript: "Shiyang River Basin (41,600 km2), the Heihe River Basin (143,000 km2), the Shule River Basin (157,000 km2), and a Desert Region (152,445 km2)"

L115-118: How do you know (e.g. the watershed area of the Rhine river is much smaller than the Hexi Corridor area)? Can you provide the SNR values for these different areas?

R15: The size of the individual basin of the Hexi Corridor is smaller than the mentioned basins, Mississippi (3,202,230 km2), Rhine (185,000 km2), Mackenzie (1,743,058 km2). The SNR values of the Hexi Corridor is approximately 2.5, compared to Mississippi (SNR $\approx$ 11), Rhine (SNR $\approx$ 17), Mackenzie (SNR $\approx$ 20).

L122: What is the difference between "surface water" and "inundated water"?

R16: The "surface water" in PCR-GLOBWB consists of river/channels, as well as lake and reservoir storages, while the term "inundated water" is conceptualized for the inundated water above the paddy field during the growing season. The terms are clearly described in PCR-GLOBWB literature (see e.g. Wada et al., 2014).

L128-129: In which way are the results validated against remote sensing?

R17: The validation is qualitatively analysed in terms of the correlation coefficient, Nash-Sutcliff coefficient, Root-Mean-Square different (RMSD). The statement will be added to the revised manuscript.

L147: The term "basin" is not appropriate.

R18: The term "basin" will be changed to "region" in the revised manuscript.

L181: "distributed hydrological model"



R19: The term "global hydrological model" will be changed to "global distributed hydrological model" in the revised manuscript.

L184-185: Also indicate the temporal resolution of the model.

R20: The statement "... and temporal resolution of 1 day" will be added to the revised manuscript.

L185-193: It is unclear, how or if at all these interactive modules for simulating water abstraction etc. have been used in this study. Clearly it was not the focus of this study. Thus I suggest removing this section incl. Appendix A.

R21: The section, including Appendix A, will be removed from the manuscript.

L197: Delete "an"

R22: "an" will be removed from the manuscript.

L208: Change "states" into "water storages"

R23: The term "states" will be changed to "water storage components" in the revised manuscript.

L219: This is rather a conceptual model.

R24: Reviewer is correct, like many numerical models, it is conceptual in nature.

L230: Explain "complete to the degree and order 60"

R25: The Earth gravity field is generally presented using a set of spherical harmonic coefficients (SHC) to a certain degree and order. The GRACE CSR product is provided the gravity model up to SHC degree and order 60. Therefore, we compute the TWS variation using the SHC complete to the maximum degree and order 60 in this study.

L259: Does this increment correspond to the monthly change in TWS?

R26: The increment is not necessarily (or linearly) corresponding to the filtered TWS change. The increment rather reflects the missing signal that was caused by the filter applied. In other words, the spatial pattern of the restored TWS change (after signal restoration process applied) is not necessarily similar to the filtered TWS change (see Fig. 4a compared to Fig. 4f).

L261: Is this the general uncertainty of GRACE?

R27: Based on the previous GRACE literature (Wahr et al., 2006; Klees et al., 2008; Dahle et al., 2014), GRACE uncertainty averaged-globally is approximately 2 cm.

L263-264: By looking at Fig. 4 this procedure seems to have mainly intensified the already existing pattern. To which extent are the temporal variations in TWS estimates influenced by this procedure?

R28: The signal is generally damped after the filter is used, results in <4 cm of the TWSV amplitude (please see Fig. 4a). The signal restoration process is used to restore the mitigated signal that was caused by the filter applied. The process restores the signal back for each iteration and the TWSV amplitude becomes $\sim$7 cm after 6 iterations (see Fig. 4f). The spatial pattern between Fig. 4a and Fig. 4f is also different (see the contour lines). As the signal restoration process acts differently (e.g., number of iteration) for different month, the temporal variations in TWSV estimates are also influenced by this procedure. Extensive discussion of the signal restoration process can be found in the given reference (e.g., Tangdamrongsub et al., 2016).

L287-289: It is well-know that global precipitation products show considerable uncertainties, which is also indicated by the low NS values. Since in-situ data is available, I suggest to correct the TRMM data product using the approach suggested by Condom et al. (2011).

R29: We agree with reviewer that correcting TRMM using the method proposed by Condom et al. (2011) is a good idea. However, since the in situ data over the Hexi Corridor is very sparse and does not cover all model grid cells, further analysis is needed



to investigate the impact of the method on the spatial distribution. Particularly, the impact on higher frequency (daily) of the precipitation data used in this study (compared to monthly of Condom et al. (2001)). Also, there might be a chance of introducing artefacts into the TRMM data in the grid cells if no in situ data is available. Therefore, we do not apply any correction to TRMM data, and use the standard error the product provided to represent the data uncertainty.

L298: Actual or potential ET?

R30: “evapotranspiration” will be changed to “potential evapotranspiration” in the revised manuscript.

L327-329: Actually, more appropriate data is available from other gauging stations in the Hexi Corridor for this study (see e.g. Zhang et al., 2015, 2016).

R31: We thank for reviewer’s information. However, we only had an access to limited ground observations by the time this study is conducted. More ground observations will be considered in future work.

L307-322: Because of this conversion method any comparison of groundwater storage changes from in-situ and GRACE observations will not be independent. This needs to be discussed in some detail. In addition, in the procedure described in Tangdamrongsub et al. (2015) two parameter were used instead of one. Please comment on this difference.

R32: Due to the fact that the estimated scale factor values are in line with the specific yield from the field observations (please also see R33), the bias of the estimated parameter from our approach can be considered small over the Shiyang River Basin. However, we understand reviewer’s concern, and therefore one additional paragraph will be added to the conclusion section as follows: “The conversion approach between the groundwater head measurement and groundwater storage is proven feasible over the Shiyang River Basin. The approach delivers comparable ranges of scale factor estimates to the specific yield estimated from the field observation. However, it is noted here that the results of the conducted validation might be over-optimistic, since the well data processed with the adopted conversion procedure are not fully independent of assimilated GRACE data. The specific yield from the field observation must be used when available." Additionally, the difference between 1 and 2 parameters are only the bias (first parameter, "a" parameter in Tangdamrongsub et al. (2015)) becomes very small (∼1e-14) when the TWS variation and head variation are considered. Therefore, Eq. (1,2) of Tangdamrongsub et al. (2015) and Eq. (2,3) in the submitted manuscript provide the same result. However, for consistency, we restore the bias term in the revised manuscript as △GWS_{GRACE-△SM}+e = b+ f·△h (2) △GWS_{in situ} = bˆ+ fˆ·△h (3)

L317-318: Please provide a figure with the data and the regression.

R33: The figure of the regression analysis is shown below (please see Fig. R1). To reduce the redundancy, we do not include Fig. R1 in the manuscript, but instead we will include a discussion of the parameter estimation in the revised manuscript as follows: "Yang et al. (2001) showed that the specific yield values obtained from the field measurements over the Shiyang River Basin was between 0.01 and 0.3. Although, the measurement was not conducted at the well stations used in this study, the values obtained can be used as a guidance of the specific yield of the Shiyang River Basin. In this study, the head measurements were converted to storage unit with the approach described in Sect. 4.3.1. The bias term in Eq. (3) was found to be very close to zero, as the variation (mean removed) was used in the regression analysis. The estimated scale factor was 0.23, 0.04, 0.24, 0.25, and 0.32 at W1 – W5, respectively, which was in line with the values obtained from the field measurement."

L320: Why are you using an averaged f value to calculate the groundwater storage for each well? I would have thought that the variations in parameter f should represent local variations in storage parameters of the aquifers. Please explain the reasoning behind this procedure.



R34: The parameter is individually estimated and used for each well location. No average parameter is used. For clarity, we will extend the statement as follows: ". . . and △GWS(GRACE-△SM) at each individual location, a bias (b), a scale factor (f) . . ."

L451: Please explain how you selected these parameters (e.g. did you use a sensitivity test?).

R35: We selected these parameters based on several previous PCR-GLOBWB studies (e.g. Sutanudjaja et al., 2011, 2014), showing that these selected parameters are indeed the sensitive ones to model simulation results. For clarity, the reference will be added to the revised manuscript.

L526-527: Change into Figure 10

R36: "Fig. 9" will be changed to "Figure 10" in the revised manuscript.

L545: "on" instead of "of"

R37: "of" will be changed to "on" in the revised manuscript.

L549-550: Please provide information on the origin of these parameter values.

R38: The origin of the parameter values is given in Sutanudjaja et al. (2011, 2014), and the reference will be given in the revised manuscript. Further information related to the origin of parameter values were provided in Appendix A of the submitted manuscript. However, they are removed based on reviewer suggestion (see R21). The model parameters of PCR-GLOBWB are derived from several globally available datasets that are listed as follows. The Global Land Cover Characteristics Data Base Version 2.0 (GLCC 2.0, http://edc2.usgs.gov/glcc/globe int.php) and and FAO soil maps (1995) were used in order to parameterize the land cover and upper sub-surface properties. For mapping aquifers and estimating the groundwater recession coefficient, the GLobal HYdrogeology MaPS (GLHYMPS) global maps of permeability and porosity (Gleeson et al., 2014), as well as available global digital elevation models (e.g. HydroSHEDS, Lehner et al., 2008) were used. For further explanation about the PCR-GLOBWB model parameterization, the reader is referred to the technical reports (e.g. van Beek and Bierkens, 2009; van Beek, 2008); and other relevant publications (e.g. Sutanudjaja et al., 2011, 2014).

L543: How do you know that the groundwater store of the Desert Region is small.

R39: We realized that the statement is misleading and we change our statement to " ...the small amplitude of the groundwater variation of this region ...". Small GWSV over the Desert Region is presented in Fig. 10k.

L553-554: Please explain in greater detail, why higher values of K_sat and lower values of J have led to a smaller amount of water addition.

R40: We realize that the interpretation the amount of water storage in terms of K_sat and J might be misleading as they do not have a linear relationship. Instead, soil water storage capacity (SC, see Table 1) and forcing data have greater impact on the water storage estimate. Note that greater SC value leads to greater amount of water stored in soil layer, and consequently lesser water percolate to the groundwater store. Therefore, we remove the statement related to K_sat and J, and change the analysis of this section to: "The impact of GRACE DA on different stores was influenced by both the model parameters and the forcing data assigned. The 4 basins have similar soil water storage capacities (see Table 3), which indicates that the basins can store similar amounts of soil water and generate similar amount of groundwater recharge under the same rainfall condition. However, the 4 basins received different amounts of rainfall and therefore resulted in different SMSV and GWSV estimates. For example, the Shiyang River Basin received the greatest amount of rainfall ($\sim$ twice of Heihe River Basin), which led to the greatest amount of the SMSV estimate ($\sim$1 cm annual amplitude). Such large amount was also sufficient to percolate into the groundwater layer, resulted in GWSV of $\sim$0.7 cm (see Fig. 10i and Table 2). In contrast to the Shiyang River Basin, the Desert Region received approximately 3 times less amount of rainfall, which led to a somewhat smaller amount of SMSV $\sim$0.7 cm (annual amplitude), $\sim$0.2 cm of GWSV



(see Fig. 10g, k)." The above paragraph will be added to the revised manuscript.

L599-600: I wonder whether the better agreement with the GRACE DA results is due to (or a least partly due to) the scaling procedure of the piezometer data. Please add a discussion on this.

R41: Due to the fact that the estimated scale factor values are in line with the specific yield from the field observations (please also see R33), the bias of the estimated parameter from our approach can be considered small over the Shiyang River Basin. However, we understand reviewer's concern, and therefore add one additional paragraph into the conclusion of the revised manuscript: "The conversion approach between the groundwater head measurement and groundwater storage is proven feasible over the Shiyang River Basin. The approach delivers comparable ranges of scale factor estimates to the specific yield estimated from the field observation. However, it is noted here that the results of the conducted validation might be over-optimistic, since the well data processed with the adopted conversion procedure are not fully independent of assimilated GRACE data. The specific yield from the field observation must be used when available."

L642: Clearly, predictions for G2 were improved to a lesser degree.

R42: We agree with reviewer. For clarity, the statement will be changed to "Lesser degree of improvements was observed at G2".

L647-648: These are very low amounts of precipitation, indicating very local precipitation events. It would be interesting to see the spatial distribution of these rainfall events and the resulting modelled soil moisture distribution.

R43: The maps of rainfall and SM storage estimates of the discussed events (September 2007, 2008) are shown below (please see Fig. R2). However, this is beyond the scope of this study, and therefore Fig. R2 is not presented in the manuscript.

L676-678: Why should the SM storage of the Desert Region decrease although precipitation shows an increasing trend? Please discuss.

R44: The discussion will be added to the revised manuscript: “In the Desert Region, in contrast to other basins, the minor decreasing TWS trend of -0.1 cm/yr was dominated by loss of SM storage. This was likely caused by inaccurate model parameter calibration over the Desert Region (i.e., too large SC value). Separation of the TWS into groundwater and soil moisture store was likely incorrect. As such, GRACE update was mostly attributed to the SM component, so that a groundwater pumping signature (Jiao et al., 2015) was seen in the SM instead of the GWS layer.” Further discussion of this (and related) issue is also included in the conclusion: “It should be emphasized that GRACE does not fix a technical problem of the hydrological model, but it rather provides information which is not available otherwise. . . .”

L712-714: Until now, there was no indication that groundwater abstraction was considered in the modelling. Please add a description. Why was the groundwater abstraction not considered in the DA?

R45: In this study, the state vector only contains the water storage. As the groundwater abstraction is a parameter of PCR-GLOBWB, it is not included in the state vector. Therefore, the groundwater abstraction is not separately estimated in this study. However, the information of groundwater abstraction is contained in GRACE observation. Once GRACE DA is applied, such information is propagated into the state vector, particularly the groundwater layer. This is clearly seen in the negative trend of updated groundwater estimates. This discussion will be included in the conclusion of the revised manuscript. “It should be emphasized that GRACE does not fix a technical problem of the hydrological model, but it rather provides information which is not available otherwise. Note that, in principle, the model may predict any long-term behaviour of water storage, but that information should be brought in "by hand" (e.g., via the groundwater abstraction parameter). As soon as that information is not available, reliable long-term predictions on the basis of hydrological modelling alone are conceptually impossible.”



L734-735: See comment above. Would it be possible to update the groundwater abstraction parameter?

R46: Yes, it is possible to update the model parameter together with the state vector. We will consider reviewer’s suggestion in the future work.

L744: Please provide quantitative information on groundwater abstraction.

R47: As the groundwater abstraction is not estimated by our GRACE DA approach, we do not quantify the amount of groundwater abstraction in this study. The groundwater abstraction can be quantified when the parameter is estimated together with the state vector.

References

Dahle, C., Flechtner, F., Gruber, C., König, D., König, R., Michalak, G., and Neumayer, K.-H.: GFZ RL05: An Improved Time-Series of Monthly GRACE Gravity Field Solutions, In Flechtner, F., Sneeuw, N., Schuh, W.-D. (Eds.), Observation of the System Earth from Space - CHAMP, GRACE, GOCE and future missions, (GEOTECHNOLOGIEN Science Report; 20; Advanced Technologies in Earth Sciences), Berlin, Springer, 29-39, http://doi.org/10.1007/978-3-642-32135-1_4, 2014.

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.

Peel, M. C., Finlayson, B. L., and McMahon, T. A.: Updated would map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 1633–1644, 2007.

Sutanudjaja, E. H., van Beek, L. P. H., de Jong, S. M., van Geer, F. C., and Bierkens, M. F. P.: Large-scale groundwater modeling using global datasets: a test case for the {Rhine-Meuse} basin, Hydrol. Earth Syst. Sci., 15(9), 2913–2935, doi:10.5194/hess-15-2913-2011, 2011.

Sutanudjaja, E. H., van Beek, L. P. H., de Jong, S. M., van Geer, F. C., and Bierkens, M. F. P.: Calibrating a large-extent high-resolution coupled groundwater-land surface model using soil moisture and discharge data. Water Resour. Res., 50, 687–705. doi:10.1002/2013WR013807, 2014.

Tangdamrongsub, N., Ditmar, P. G., Steele-Dunne, S. C., Gunter, B. C., and Sutanudjaja, E. H.: Exploring irregular flood events over Tonlé Sap basin in Cambodia using GRACE and MODIS satellite observations combined with altimetry observation and hydrological models, Remote Sens. Environ., 181, 162 – 173, http://dx.doi.org/10.1016/j.rse.2016.03.030, 2016.

Wada, Y., Wisser, D., and Bierkens, M. F. P.: Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth System Dynamics, 5, 15–40. doi:10.5194/esd-5-15-2014, 2014.

Wahr, J., Swenson, S., and Velicogna, I.: Accuracy of GRACE mass estimates, Geophys. Res. Lett., 33, L06401, doi:10.1029/2005GL025305, 2006.

Zhu, J. F., Winter, C. L., and Wang Z. J.: Nonlinear effects of locally heterogeneous hydraulic conductivity fields on regional stream–aquifer exchanges, Hydrol. Earth Syst. Sci., 19, 4531–4545, 2015.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-354, 2016.



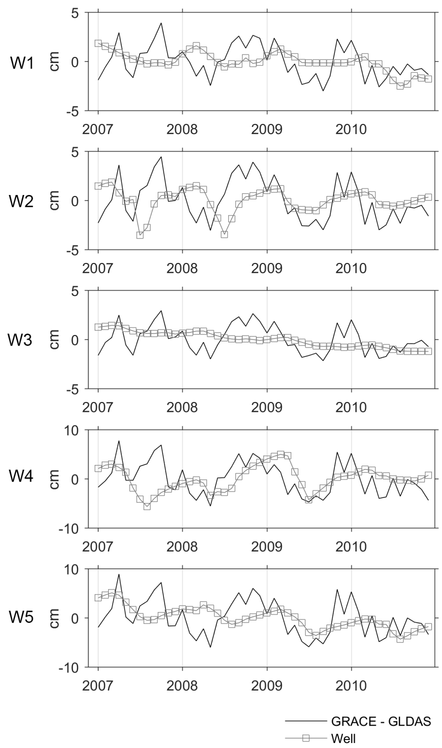


**Fig. 1.** Figure R1. Regression analysis between GRACE-GLDAS and adjusted well measurements in 5 different locations.

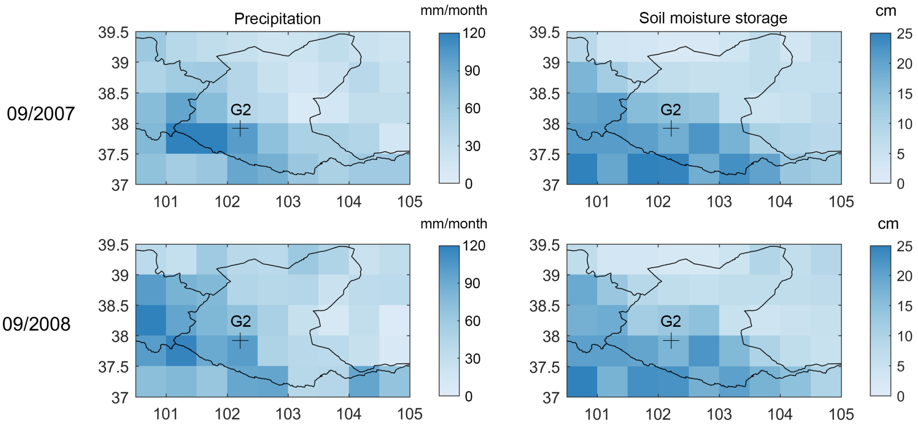


**Fig. 2.** Figure R2. Monthly total precipitation (left) and SM storage estimates of September 2007 and 2008. Stream gauge location G2 is also shown.