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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Estimation of hydrological drought recovery based on GRACE water storage deficit" *by* Alka Singh et al.

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Summary: The presented work shows an integrated precipitation approach to determine the re- covery period and required precipitation to refill water storages and thus to overcome a hydrological drought. Thus, historical integrated precipitation is linked to total wa- ter storage anomalies (TWSA) by GRACE to combine and validate their precipitation- based methodology to an existing storage deficit methodology. Furthermore, three scenarios of precipitation forecast are provided to identify the best estimated time of re- covery. They found that the recovery period of integrated precipitation is in good agree- ment with the recovery period from TWSA, especially in regions where integrated pre- cipitation and total water storage changes showed a strong linear relationship. I think that this work discusses an important topic to have a better under-

standing of drought evolution and to use this information possibly in water management. The methodology and findings are of good scientific quality and significance, but yet I have general and specific concerns, especially regarding to presentation quality, that are listed below. Thus, I recommend major revision, but believe that the manuscript could be published after addressing/clarifying my comments.

Response: We agree and thank the reviewer for guiding the paper in such a detail to improve clarity and focus.

General comments 1. Until the first results were shown, it was not clear if the precipitation or the GRACE approach is the main contribution of the paper. This is important for abstract, introduction, conclusion and maybe should also be more consistent with the title and structure of the data and methods chapter. For example, [Page1 Line14] says the main goal is the combination of GRACE and precipitation, while [Page1 Line21] let assume that the author's main point is the precipitation approach and GRACE is only used as validation.

Author's response: We thank the reviewer for bringing this up. The paper uses both GRACE and GPCP equally, therefore, the title is modified as 'Estimation of hydrological drought recovery based on precipitation and GRACE water storage deficit'. GRACE is also used for validation but the main focus of this work is drought recovery estimate based on required precipitation, which is estimated from GRACE. We added a line in the introduction for more clarity. "The intellectual contribution of this paper is in the estimation drought recovery and conceptually bringing a framework for drought recovery forecast based on precipitation deficit. "

2. More clarification is needed about the drought definitions. Do you place your approach more in the context of hydrological drought or drought in general? The manuscript should be consistent according to the drought definitions. Be also clear about other drought categories of parameters, e.g.: [Page 1 Line32] meteorological drought is not only described by precipitation, also evapotranspiration. [Page1 Line34]

soil moisture, precipitation, and runoff and not all hydrological parameters. For example, precipitation is a meteorological parameter.

Author's response: A sentence is modified in the introduction to clarify that the study is more in the context of hydrological drought. ' This study focusses on hydrological drought, which requires, combining both surface (snow and surface water), and subsurface (soil moisture and groundwater) hydrological information. ' Thanks for pointing it, we modified the drought categories of parameters as 'including agricultural (soil moisture deficit), meteorological (eg. precipitation deficit or increase in evapotranspiration), and hydrological (storage deficit for eg. in streamflow/groundwater) droughts.'

3. Why are mascons used instead of spherical harmonics, the mascon solutions are underlying by constraints. Does the cap size of 3 x 3 degree of mascon solution then not represent a similar spatial resolution as the spherical harmonic GRACE resolution?

Author's response: The GRACE analysis in this paper is based on climatological anomalies of the three monthly smoothed and detrended TWS signal, therefore fine differences between different GRACE solutions after all these postprocessing gets minimized. Mascon based GRACE product has a relatively similar spatial resolution (3x3 deg) as that of GPCP (2.5x2.5deg). Section 2.2 talks about it, Section 2.2 talks about it, "The spatial resolution of the original GRACE solution (3-degree mascon) and GPCP (2.5-degree) are comparable. However, as mascon size varies with latitude, therefore to improve the interpretation both datasets are brought to the 0.5-degree grid. " However, we also acknowledge the spatial difference between them at different latitudes.

4. [Page3 Line103] Which method is used to regrid the data? Is there a precipitation data set with an 0.5-degree resolution? I ask myself if the downscaling from 2.5 to 0.5 degree has a significant impact.

Author's response: We used bilinear interpolation to regrid the GPCP data, in order to harmonize it with the GRACE grid. We agree with the reviewer's concern that it won't add any information by re-gridding 2.5 degree to 0.5 degrees and there are many pre-

cipitation products like CRU, GPCC, etc. However, GPCP is the best available global precipitation data, considering its spatial coverage, a combination of i-situ and remote sensing observations, and a longer time frame. GPCP combines the strength offered by in situ as well as satellite data. In many regions of the world in situ data are sparse, so using a product that only utilizes in situ data may not be the best choice. GPCP applies gauge under catch correction to in situ precipitation measurement, which has been found important to improve snowfall measurement (Behrangi et al. 2018). Besides, in section 3.3 historical analysis of the data is done using 1979-2017 precipitation data. For this period GPCP is the best available data.

Behrangi, A., A. Gardner, J. T. Reager, J. B. Fisher, D. Yang, G. J. Huffman, and R. F. Adler (2018), Using GRACE to Estimate Snowfall Accumulation and Assess Gauge Undercatch Corrections in High Latitudes, Journal of Climate, 31(21), 8689-8704, doi: 10.1175/jcli-d-18-0163.1.

[Page3 Line110] Why are the TWSA smoothed with an averaging filter? Does their noise have a significant impact on the results? Author's response: As drought develops in a smooth progression and we are looking for the amount of missing mass in a system caused by drought. Therefore, a 3months moving average is considered a better representation of the progression of drought. Monthly observations also have a similar relationship between TWS and precipitation but signals are neat and more intuitive after averaging filter.

5. [Page4 Line129-136] The linkage between integrated precipitation and GRACE is an important aspect for the validation so it should be explained more detailed. The paragraph is (probably) based on the water balance equation, which should at least be mentioned but better also shown. The assumptions that were decided to describe the relationship about evapotranspiration/runoff should be added here and it also should get clear how the precipitation is integrated in time. So for example, is it integrated continuously for each month to the previous months, or is there an integration period of 3 months that is running over all months, etc.?

Author's response: We understand the reviewer's point and added the following lines: " dS/dt = P – ET – R Eq. 1

The water balance equation based on hydrological fluxes (Eq. 1) shows that the change in terrestrial water storage (dS) in a region for a given month (dt) depends on the monthly precipitation (P, mm/month); evapotranspiration (ET, mm/month) and the streamflow (R, which includes both surface water and subsurface water) (Swenson and Wahr, 2006). We assumed the relationship between P and (ET + R) remains constant for a region. Accordingly, the variability in precipitation shows the possible variation of storage in a month. Therefore, the amount of required-precipitation to overcome a deficit can be estimated using the association between precipitation and TWSA." Swenson, S. and Wahr, J.: Estimating Large-Scale Precipitation Minus Evapotranspiration from GRACE Satellite Gravity Measurements, J. Hydrometeor., 7(2), 252–270, doi:10.1175/JHM478.1, 2006.

6. [Page4 Lines144-147 and Lines158-162] It was not clear how the required precipitation is linked to the regression coefficients. It would great if the linkage for the example of a coefficient lower/higher/equal 1 in the first paragraph is clearly explained. Secondly, how do we then get the surplus required-precipitation? Is it derived by removing cdPA from dTWSA?

Author's response: It is a great idea; we added a small description: "Based on the linear relationship between dTWSA and cdPA the required precipitation has been estimated. Regression coefficients greater than 1 means the required precipitation is more than the amount of missing water. It is because precipitation lost in other hydrological processes like evapotranspiration, runoff (Eq.1) is not observed by storage variability. Coefficient equals to 1 means the amount of required precipitation is the same as that storage loss, which means there is no other dominant process in that region. Coefficient less than 1 are the regions of weak precipitation-storage coupling, which can be due to other physical processes like melting of snow/frozen surfaces, groundwater extraction, irrigation, etc (non-red regions in Figure 2a)"

Figure 4, as well as some other figures, is analyzed too shortly (e.g. [Page5 Line181]) or, for example, only part a) of a), and b) is described. The figures provide much more information, especially about spatial differences. So, the figures should be described more in detail, which I prefer because they contain interesting findings, or removed/added to supplementary.

Author's response: We agree with the reviewer's point and added small description of the figure. "Figure 4 shows the fractional variance of the decomposed signal. For most regions annual signal dominates in precipitation (Figure 4a). However, regions where the wet season is not explicit in their climatology, high-frequency signal plays a major role, for example in central Europe, eastern Siberia, western N. America, southern Australia, etc. (Figure 4c). Contrarily, the long-term signal obtained by combining linear trend and the inter-annual signal has the least variability globally (Figure 4b). These smooth signals are driven by climate indices like El Niño southern oscillation (ENSO), Pacific decadal oscillation (PDO), and the North Pacific mode (NPM), etc. (Özger et al., 2009). The annual and long-term signals are directly applied for the signal reconstruction with the assumption that a similar trend will continue. Özger, M., Mishra, A. K. and Singh, V. P.: Low-frequency drought variability associated with climate indices, Journal of Hydrology, 364(1), 152–162, doi:10.1016/j.jhydrol.2008.10.018, 2009"

7. [Page5 Line188] It is not clear how the sub-seasonal signal is computed and where the number of 0 to 3 months of reconstruction is resulting from. The final hindcast is 2 years, so how did the authors manage the 0-3 months restriction of the sub-seasonal signal?

Author's response: Based on the possible confusion the reviewers pointed out, we added a sentence. "Sub-seasonal signal is obtained from the residual of inter-annual signal. This high-frequency signal has 0-3 months of temporal autocorrelation; accordingly, we have limited skill in synthesizing sub-seasonal signal."

8. [Page7 Line247] The definition of severe drought was not exactly set. What is the

definition or to which definition is it referred? Author's response: We added a line to make it clear. Thanks "Here, severity of a drought defined by the amount of water shortage per month."

[Page7 Line253] Based on which principles are the differences of recovery months divided into the different classes? How were the classes determined? It leads also to confusion in Figure 9. Without reading the caption it seems as if the difference is very small everywhere (from 1 to 4 months), but the number does not represent the "difference in months", rather the "class number of differences in months". Author's response: Y-label of the Figure-9c is modified (thanks for pointing it). The first two classes are defined by 2 months difference, as the majority of regions have less difference than the third class has 4 months difference and the last class has no upper limit.

9. [Page9 Line333] Could you please discuss that the recovery period derived from precipitation is also underlying certain assumptions (e.g. about evapotranspiration)? Author's response: We added the following line. "As discussed in Section 3.2, the underlying assumption of this work is that the relationship between precipitation, runoff, and evaporation for each location will remains unchanged. The required precipitation is derived from the GRACE observations, it inherits the relationship between P and ET based on equation 1. Therefore, the estimated required precipitation includes the impact of evaporation and runoff loss. "

Specific comments I would recommend working through the manuscript again to remove grammatical/syntactic errors. Some examples: - [Page1 Line30] Missing commas, 'the', and 'and/or' (should also be checked: and/or is needed before last item of a list), suggestion: '. . . developing parts of the world, for example, the 2011 East Africa drought or the 2018 dry corridors of central America (REF).'

Author's response: Thanks for pointing it, we have modified and added references as following: "example the 2011 East African drought (Lyon and DeWitt, 2012) or the 2014-16 dry corridors of central America (Guevara-Murua et al., 2018) Lyon, B. and

DeWitt, D. G.: A recent and abrupt decline in the East African long rains, Geophysical Research Letters, 39(2), doi:10.1029/2011GL050337, 2012. Guevara-Murua, A., Williams, C. A., Hendy, E. J. and Imbach, P.: 300 years of hydrological records and societal responses to droughts and floods on the Pacific coast of Central America, Clim. Past, 14(2), 175–191, doi:10.5194/cp-14-175-2018, 2018."

- [Page2 Line56] have/has and "the" too much, suggestion: '. . . is independent of other drought indices and has global spatial coverage.'

Author's response: Thanks for the correction, we have modified it as "The GRACE-based drought index is independent of the meteorological estimates and their combined uncertainties"

- [Page2 Line69] singular/plural, citing brackets, suggestion: '. . . reviewed different kinds of drought and their prediction methods based on statistical, dynamical, and hybrid methods. Panet et al. (2013) were ...' – Author's response: Corrected the citing bracket and singular/plural

[Page3 Line91] add the date of last access for websites – Author's response: Added the access date

[Page4 Line146] be consistent with required precipitation/required-precipitation – [Page 5 Line 181] be consistent with figure/Figure and section/Section - [Page5 Line190] estimated precipitation → reconstructed precipitation - [Page5 Line202] be consistent with climatology/annual signal Author's response: Changed to a consistent expression. Thanks!

References that should be added: - [Page2 Line59] Reference for global gridded assessments – Author's response: We added the following reference added (Gerdener et al., 2020; Li et al., 2019) Li, B., Rodell, M., Kumar, S., Beaudoing, H. K., Getirana, A., Zaitchik, B. F., Goncalves, L. G. de, Cossetin, C., Bhanja, S., Mukherjee, A., Tian, S., Tangdamrongsub, N., Long, D., Nanteza, J., Lee, J., Policelli, F., Goni, I.

B., Daira, D., Bila, M., Lannoy, G. de, Mocko, D., SteeleâĂŘDunne, S. C., Save, H. and Bettadpur, S.: Global GRACE Data Assimilation for Groundwater and Drought Monitoring: Advances and Challenges, Water Resources Research, 55(9), 7564–7586, doi:10.1029/2018WR024618, 2019. Gerdener, H., Engels, O. and Kusche, J.: A framework for deriving drought indicators from the Gravity Recovery and Climate Experiment (GRACE), Hydrology and Earth System Sciences, 24(1), 227–248, doi:https://doi.org/10.5194/hess-24-227-2020, 2020.

[Page2 Line62] Reference for increasing frequency of drought – Author's response: Following reference added (Cook et al., 2014) Cook, B. I., Smerdon, J. E., Seager, R. and Coats, S.: Global warming and 21st century drying, Clim Dyn, 43(9), 2607–2627, doi:10.1007/s00382-014-2075-y, 2014.

[Page3 Line98] Reference for cubic convolution interpolation Author's response: Reference added (Keys, 1981) Keys, R.: Cubic convolution interpolation for digital image processing, IEEE Trans. Acoust., Speech, Signal Process., 29(6), 1153–1160, doi:10.1109/TASSP.1981.1163711, 1981.

[Page2 Line77] Please explain why only terrestrial water storage can be used instead of, for example, in-situ groundwater data. Author's response: We added a sentence. Thanks "With the sparse availability of in-situ groundwater observations and limited soil moisture observations upto top 5cm of the soil, complete profile of the water stored in a column can only be obtained from the GRACE-based terrestrial water storage."

[Page2 Line81] It could be added that you focus on sub-decadal drought because there are only about 15 years of GRACE data. Author's response: We modified the sentence. Thanks again! Here, we focus on sub-decadal drought only because of the availability of GRACE data for 15 years. The study can be extended for a longer time frame with the GRACE- follow on observations.

[Page2 Line83] GPCP was not introduced yet. Author's response: Added: Global Precipitation Climatology Project (GPCP)

[Page3 Line114] "Here, we define 'recovery' as a return to the climatological storage state for a given month." This is not totally clear to me, does it mean that the deviation from current dTWSA to the climatology itself in a specific month, which is referred to as severity in Thomas et al. (2014), is already the recovery? Author's response: Yes, decrease in severity is recovery.

[Page3 Line123] state of drought → severity of drought? Author's response: severity of drought changed to intensity of drought

[Page4 Line125] Could you mark the three recovery periods in Figure 1, please? It seems as if the recovery periods are longer than 1.5, 1 and 0.5 years. Author's response: oh yes! you are right. each grid is two years so it is almost 4, 2 and 1 years. We corrected it. Thanks for pointing. [Page5 Line167] ... are statistically analyzed using the methods of . . . Author's response: Added: using signal decomposition

[Page5 Line187] How was the number 10-14 months for autoregression chosen? Author's response: Based on the duration of significant auto-correlation with inter-annual signal.

[Page5 Line184] The annual signal and linear trend extracted by signal decomposition [Page5 Line200] worst → worse. [Page5 Line201], [Page7 Line271], and [Page7 Line283] etc.: 'In these regions...', 'this region', and 'monsoon regions' be precise which regions. [Page5 Line202] robust → dominant Author's response: corrected. Thanks!!

[Page6 Line211] Where (reference) is it defined that one sigma represents a wet year and three sigma an exceptionally wet year? Author's response: We assumed it, to generate three precipitation scenarios. The sentence is modified accordingly. "We assumed that one standard deviation wetter than normal precipitation as wet month and three standard deviations wetter than normal precipitation as exceptionally wet month."

[Page6 Line220] providing a minimum and maximum baseline? Author's response:

Even in exceptionally wet scenario in dry season, system fails to recover. Therefore, it does not provide maximum baseline.

[Page6 Line232] “In Figure7, observed precipitation (red dashed line) and absolute required precipitation (blue line) ...” This was already said. Author’s response: Deleted. Thanks for pointing it. Figure 7: This was quite hard to analyze. I would recommend to enlarge the subfigures or put them in a different order (e.g. 4 x 1). Author’s response: Modified most of the figures.

[Page6 Line241] some drought → drought [Page6 Line241] Remove ‘it is a random selection of the month for’ Author’s response: Removed, thanks! [Page7 Line254] blue → red? Author’s response: Corrected blue to red.

[Page7 Line256] Is with 80% the total global land area or the masked global land area meant? Author’s response: Masked global area. Added the word ‘masked’. Thanks! 4.2.2 Different precipitation scenario → Precipitation scenarios

[Page7 Line 265] ‘We stimulated one-month (February 2016)recovery period ...’ Not clear what is meant Author’s response: This section shows the recovery percentage within a month based on the three-precipitation scenario.

[Page8 Line288] Better more precise: Here we define drought severity and duration using ... Author’s response: Added ‘drought intensity and duration’ 5 Discussion: Refer to section if different aspects/findings are discussed. [Page8 Line298] soil water column → water column Author’s response: Deleted ‘soil’, thanks! [Page8 Line 299] The Position of the sentence in paragraph awkward in the previous context. Author’s response: Deleted the sentence. Thanks! [Page9 Line327] Also shown in Figure 11 . . . Author’s response: Added (as shown in figure 8)

[Page9 Line342] 1) the independence from other drought indices → more precise, which independencies? Author’s response: Added names of indices (PDSI, SPEI, SPI) and independency from the uncertainties of different meteorological variables and their

complex interactions. Thanks

All Figures: Please check figure references in the text, some of the references have been mixed up. Make sure that all figure captions and title really describe what is shown (compared to what) e.g. Figure 4 fraction of a), b), and c) to what? Total of all. . . or Figure 9 validation of what by what? And consider changing colorbars, since some figure might better be represented in a different way, e.g. Figure 9 discrete colorbar. Author’s response: Modified most of the figures, please see the attachment. Many thanks for the very detailed review and constructive comments.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-590, 2019.

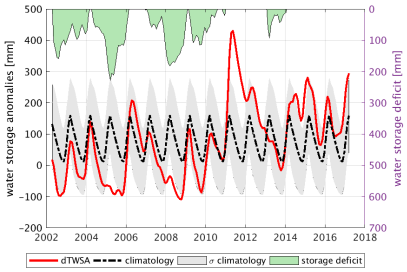

Figure 1: Water storage deficit from GRACE: The smoothed and detrended TWSA (dTWSA in red plot) is reduced by its climatology (black plot), to estimate deviation from the climatology. The negative residuals from the climatology are plotted on the upper axis as a green shaded area and scaled on the right side. The grey shade indicates ±1 standard deviation of the climatology.

Fig. 1.