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

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We highly appreciate the reviewer for extensive and generous comments on the manuscript. Please find below the response. The modifications in the manuscript are shown within quotation marks.

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 esti-

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mated time of recovery. 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 understanding 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 detail to improve its 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. Added a line "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. " (line 109)

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.' (line 42) drought categories of parameters are modified: "including agricultural (soil moisture deficit), meteorological (eg. precipitation deficit or increase in evapotranspiration), and hydrological (storage deficit for eg. in streamflow/groundwater) droughts." (line 40)

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 gets minimized. Underlying information of mascon and SH solution is same but in the equatorial region Mascon shows higher spatial resolution. Additionally, mascon based GRACE product have a relatively similar spatial resolution (3ïĆřx 3ïĆř) as that of GPCP (2.5ïĆřx 2.5ïĆř), so we selected Mascon solution.

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: GPCP is a widely used global precipitation data. In section 3.3

historical analysis 1979-2017 of the precipitation data is done. For this period GPCP 2.5degree is the best available data which is interpolated to 0.5 degree by using the bilinear method to harmonize it with the GRACE grid. There are many higher resolution precipitation products like TRMM, CRU, GPCC, etc. However, GPCP combines the strength offered by in situ as well as satellite data to obtain global picture while others are limited to 60 degrees North and South latitudes. Additionally, 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 Under catch Corrections in High Latitudes, Journal of Climate, 31(21), 8689-8704, doi: 10.1175/jcli-d-18-0163.1. Added in the manuscript (line 140) "Global Precipitation Climatology Project (GPCP) is a widely used global precipitation data. Most of the other observational products don't produce precipitation estimates beyond 60deg S/N for longer historical period (1979 – present). Besides, GPCP applies gauge under catch correction to in situ precipitation measurement, which has been found important to improve snowfall measurement." (Behrangi et al., 2018)

5. [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 better interpretable with averaging filter.

6. [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). Assuming the relationship between precipitation and ET + R remains constant for a region, the variability in precipitation gives an idea of possible variation in the storage 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. " (line181)

7. [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. This 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 the 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)." (line 210)

8. 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 a small description of the figure. "Figure 4 shows the fractional variance of the decomposed signal. For most regions, annual signals dominate 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 NinÌČo southern oscillation (ENSO), Pacific decadal oscillation (PDO), and the North Pacific mode (NPM), etc. (OÌĹzger 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. " OÌĹzger, 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" (line 260)

8. [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: A sentence added "The sub-seasonal signal is obtained from the residual of the inter-annual signal. This high-frequency signal has 0-3 months of temporal autocorrelation; accordingly, we have limited skill in synthesizing sub-seasonal signal." (line 275)

9. [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: Added the following sentence "Here, the severity of a drought defined by the amount of water shortage in a month." (line 348) [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: Label of the figure is modified (thanks for pointing). 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.

10. [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: The underlying assumption of this work is that the relationship between precipitation, runoff, and evaporation for each location will remain unchanged. As 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 to work through the manuscript again to remove grammatical/syntactic errors. Some examples: - [Page1 Line30] Missing com-

mas, ‘the’, and ‘and/or’ (should also be checked: and/or is needed before the 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: Modified and references added “example the 2011 East African drought (Lyon and DeWitt, 2012) or the 2014-16 dry corridors of central America (Guevara-Murua et al., 2018) .” - [Page2 Line56] have/has and “the” too much, suggestion: ‘. . . is independent of other drought indices and has global spatial coverage.’

Author’s response: Modified the sentence. “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 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 References that should be added: - [Page2 Line59] Reference for global gridded assessments – Author’s response: Reference added (Gerdener et al., 2020; Li et al., 2019) [Page2 Line62] Reference for increasing frequency of drought – Author’s response: Reference added (Cook et al., 2014) [Page3 Line98] Reference for cubic convolution interpolation Author’s response: Reference added (Keys, 1981) [Page2 Line77] Please explain why only terrestrial water storage can be used instead of, for example, in-situ groundwater data.

Author’s response: A line added. “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.” (line 105)

[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: Modified the line as below: "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. "(line 115) [Page2 Line83] GPCP was not introduced yet. Author's response: corrected as 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, the 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: Thanks for pointed out. Yes, each grid is two years so it is almost 4, 2 and 1 years. [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 the 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 [Page6 Line211] Where (reference) is it defined that one sigma represents a wet year and three sigma an exceptionally wet year? Author's response: These conditions are assumed in to generate three scenarios, the sentence is modified accordingly. "one standard deviation wetter than normal precipitation is assumed as a wet month and three standard deviations wetter than normal precipitation is assumed as an exceptionally wet month." [Page6 Line220] providing a minimum and maximum baseline? Author's response: Even in

exceptionally wet scenarios in the dry season, the system fails to recover. Therefore, it does not provide a 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 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 [Page6 Line241] some drought → drought Author’s response: Deleted ‘some’ [Page6 Line241] Remove ‘it is a random selection of the month for’ Author’s response: Removed [Page7 Line254] blue → red? Author’s response: Corrected the color [Page7 Line256] Is with 80% the total global land area or the masked global land area meant? Author’s response: Masked global area. 4.2.2 Different precipitation scenario → Precipitation scenarios Author’s response: Modified [Page7 Line 265] ‘We stimulated one-month (February 2016) recovery period ...’ Not Author’s response: Modified as "This section shows the recovery percentage within a month based on the three precipitation scenarios." [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’ [Page8 Line 299] Position of sentence in paragraph awkward in the previous context. Author’s response: Deleted the sentence [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). 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.

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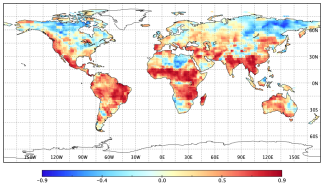
a. Correlation coefficients



b. Regression Coefficients

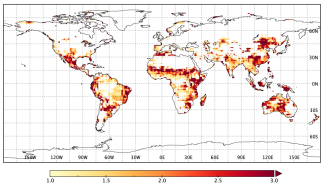


Figure 2: a) Correlation coefficients and, b) regression coefficients between cumulative detrended precipitation anomalies (cdPA) and detrended terrestrial water storage anomaly (dTWSA).

Fig. 1. figure2

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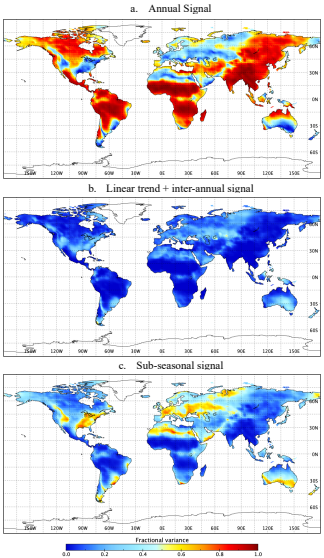

Figure 4: Fractional variance of the decomposed signal to the full signal. a. Annual Signal, b. Long-term signal, c. sub-seasonal high frequency signal

Fig. 2. figure3

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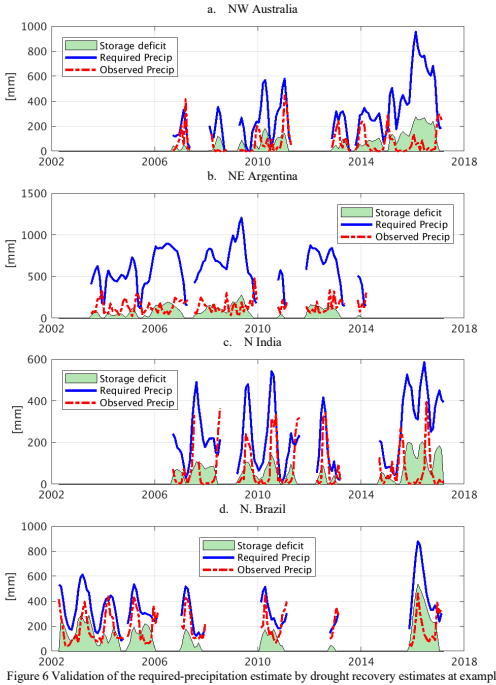

Figure 6 Validation of the required-precipitation estimate by drought recovery estimates at example locations. The different instances of drought show that drought ends (from the perspective of TWSA) whenever observed precipitation (red plot) exceeds the required-precipitation (blue plot).

Fig. 3. figure6

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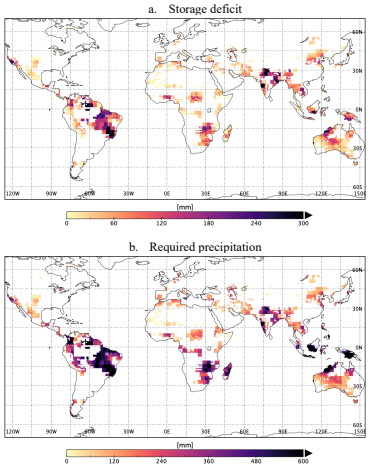

Figure 7: a) Storage deficit in an example month (January 2016). b) the amount of required-precipitation to fill the deficit.

Fig. 4. figure7

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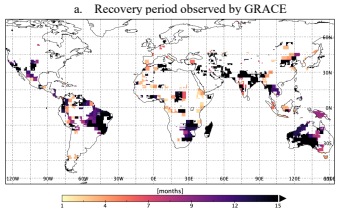

Figure 8: Validation of the estimated required-precipitation by the recovery duration from January 2016 drought observed from: a) GRACE and b) estimated by the discussed method using GRACE and GPCP observations (middle panel). c) consistency in the observed recovery duration by GRACE and GPCP (1 = 1-2 months difference, 2 = 3-4 months difference, 3 = 5-8 months difference and 4 = 9+ months difference).

Fig. 5. figure8

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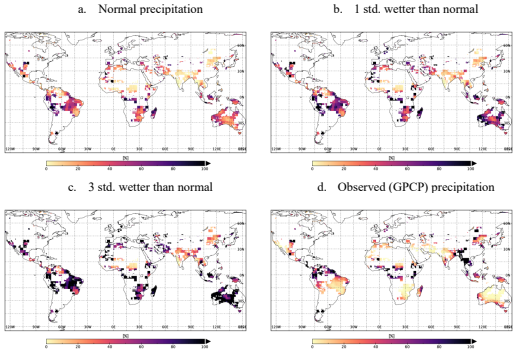

Figure 10: Expected percent recovery in a month given the three different precipitation scenarios and the observed GPCP precipitation.

Fig. 6. figure9

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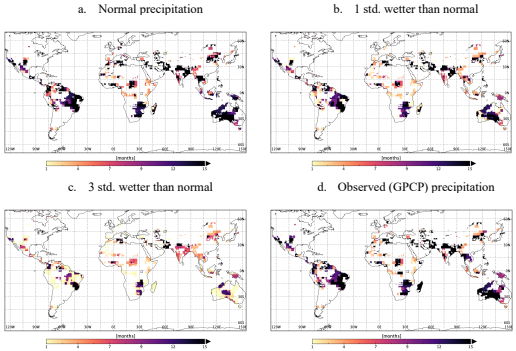

Figure 10. Duration of drought recovery from January 2016, given the three different precipitation scenarios and as observed by GRACE

Fig. 7. figure10