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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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We appreciate the constructive comment. We went over the paper and tried to improve it by adding more clarification and improving the figures. The modifications in the manuscript are put under quotation marks.

The authors devise a novel method for estimating intradecadal drought recovery periods using GRACE and precipitation data globally. The total water storage estimates from GRACE are used to determine the deficit and the precipitation data is used for estimating the drought recovery periods using an empirical forecasting model. The issue is an important one in the context of ongoing climate change. Furthermore, the subject matter is also relevant for the journal and its audience. Having said that there

are methodological issues in the data analysis which I will point out in the subsequent section, and the manuscript requires improvement in its narrative.

1.The title does not fully reflect the content of the manuscript. Firstly, the work only looks at short-term (intradecadal) droughts and secondly it uses precipitation in addition to GRACE to estimate the drought recovery times. These two aspects of the manuscript should be reflected in the title. Currently, going by the title, the drought recovery time is solely estimated from GRACE, which is incorrect.

Author's response: Thanks for bringing this up, we have modified the title as follows: 'Estimation of hydrological drought recovery based on precipitation and GRACE water storage deficit.'

2.The central goal of the manuscript seems to be to determine drought recovery times and that is facilitated by precipitation forecasts, and the majority of the manuscript is dedicated to figuring out an empirical way to predict precipitation. However, in the conclusions there is hardly any mention of precipitation and the empirical forecast model, and their role in drought recovery times. Rather it is concluded that the one of the findings is that GRACE can be used to derive drought indices, which appears to have been established by Thomas et al (2014).

Author's response: We understand the reviewer's concern. We mentioned in the manuscript that the precipitation forecast is not the focus of this work, so we preferred not to discuss it. The main idea of precipitation prediction is to generate 3 scenarios and it is mentioned. Section 3.3 states that 'Note that the motivation for providing a precipitation forecast here is not to present a state-of-the-art precipitation prediction, but to demonstrate the potential utility of the terrestrial water storage deficit in determining required-precipitation and estimating a likely time to recovery. This methodology could be augmented with any type of more complex precipitation forecasting approaches.' I agree, Thomas et al (2014) has already established that GRACE can be used to derive drought indices. However, the conclusion states that the 'GRACE based drought index is valid to estimate the required-precipitation for drought recovery.'

3. Throughout the manuscript it is not clear as to what type of drought the authors are trying to quantify. In the title it is indicated that the authors are concerned about hydrological droughts, but nothing much is said in the manuscript. In the introduction they specify there are multiple definitions of droughts, but beyond that there is no indication on what sort of droughts the authors are interested in and which sorts will be sensitive to the method developed in the manuscript. It would be beneficial if the authors clarify this for the readers.

Author's response: Thanks for bringing this up, we modified a sentence in the introduction. ' This study focusses on hydrological drought, which requires, combining both surface (snow and surface water), and subsurface (soil moisture and groundwater) hydrological information. '

4. For the data the authors use GRACE JPL mascons for total water storage and GPCP for precipitation. Given the wide variety of data available both for total water storage (CSR mascons, GSFC mascons, CSR, GFZ, JPL, ITSG spher- ical harmonics, COST-G combined solutions) as well as precipitation (GPCC, CRU, Delaware), it would be interesting to know how different the drought recov- ery times would be if we were to choose a different pair of datasets. At least in the case of GRACE it should be tested, because it is the starting point for the method proposed in the manuscript. Given the lack of consensus on which GRACE flavour is to be used, or how to reconcile the data, it is worthwhile to perform this test.

Author's response: We understand the reviewer's concern. However, 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. Mascon based GRACE product have approximately similar spatial resolution (3ïĆřx 3ïĆř) as that of GPCP (2.5ïĆřx 2.5ïĆř). Section 2.2 talks about it. Yes, we agree, there are many precipitation products like CRU, GPCC, etc. However,

GPCP is a widely used global precipitation data. 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 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 in 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. The GRACE and the GPCP datasets are represented on 3âŮę spherical cap and 2.5âŮę $\times$ 2.5âŮę equi-angular grid. After indicating that the area of the unit representations are comparable, they represent the two datasets on a 0.5âŮę $\times$ 0.5âŮę grid to perform the analyses. There a couple of issues here. Firstly, the difference between the areas of the unit representations are at best $\approx$ [10, 000]km2 (at the equator) and at worst $\approx$ [80, 000]km2 (close to the poles). Secondly, by regridding them to a smaller grid size, they are only making map a bit smooth, but there is no change in the information content. The best way to bring them to a commensu- rate resolution to perform the data analysis would have been to filter them with a common filter either a Gaussian or any other contrast preserving filter, and then regrid them to any other grid size they wanted. It is essential that the authors discuss the impact of these data processing choices on the final results.

Author's response: Thanks for bringing it so precisely. The mascon solution in the study is re-gridded by multiplying it with a scaling factor, to improve the interpretation of signals at sub-mascon resolution. This is essential as the shape and size of mascon changes with latitude. We agree that there are significant differences between the mascon (3x3 grid) and GPCP (2.5) area at different locations. The Following sentence is added in section 4.2.1, thanks for the comment with numbers. 'Though GRACE mascon and GPCP 2.5 degree are considered as comparable, nevertheless areas of the unit representations are different at different locations like at equator ≈ 10, 000 km2 and close to poles 80, 000 km2. However, as drought is a smooth process the impact of neighboring pixels should not affect the analysis significantly.'

Based on these comments I recommend a major revision. 3 Technical comments 30 Please provide references for the events you have described Author's response: Reference 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)

32 Please provide standard references for the drought definitions, for e.g., Wilhite and Glanz (1985). Water International Author's response: Added (Wilhite and Glantz, 1985)

33 It is not clear what you want to convey by indicating the different indices. Author's response: In this study GRACE TWS is used as a drought index, therefore it is essential to describe some other common drought indices and their limitations. The paragraph has been restructured to make it more clear.

38 Similar is the case for remote sensing data based drought indicators. Please clarify to the reader what their benefits and shortcomings are in order to get a perspective. Author's response: Thanks, we added a line in the introduction With the sparse availability of in-situ groundwater observations and limited soil moisture observations (up to top 5cm of the soil), a complete profile of the water stored in a column can only be obtained from the GRACE-based terrestrial water storage.

51 "This method can improve ..." until the end of line 55. Please corroborate the statement, if it is not a conclusion of Thomas et al (2014). Author's response: The lines are moved to a paragraph below to separate it from Thomas et al. paper discussion and a line added to it. . . . This quantification of total required storage for drought recovery can only be estimated using GRACE observation.

59 "... are still a few" Please cite some of those studies Author's response: Reference added (Gerdener et al., 2020; Li et al., 2019)

63 successive –> next Author's response: Changed

74 "However, above average ..." until end of line 77. Please clarify whether it is your opinion or a conclusion of Pan et al (2013) Author's response: The following line is added to separate it from Pan et al paper. Pan et-al., approach is exclusively precipitation based, however, . . .

84 In general, the introduction lacks a cogent narrative. It is hard to identify what issue you are trying to address Author's response: 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. "

88 "... global and regional water cycle." Please provide a reference for the same. Author's response: Added "global (Eicker et al., 2016; Fasullo et al., 2016) and regional water cycle (Singh et al., 2018; Springer et al., 2017)." 104 When you say comparable, please indicate the numbers. Author's response: we discussed that 3 degree Mascon and 2.5 degree GPCP data products are comparable in spatial terms. Additionally, as per your suggestion area details are added in the section 4.2.1

135 Please clarify to the reader why you need to integrate the precipitation time- series. Modified the line as follows: "The smoothed and detrended precipitation anomaly is then integrated in time to get storage anomaly, which is termed as cumulative detrended smoothed precipitation anomaly (cdPA)."

142 The variability of precipitation intensity can be checked. It is unclear why this needs to be assumed. Author's response: This assumption is for the estimation of required precipitation to consider the relationship between precipitation and storage variability stable. For example, a region having mostly slow rain has one kind of storage-precipitation relationship and if it gets unusual heavy rain then the relationship changes. Therefore, we assume here, that there is less variability in the precipitation intensity of a region.

189 The paragraph reads like the caption of Figure 5. Please interpret the figure for the reader as to what you want to convey through that figure. Author's response: Thanks, a couple of sentences added. This precipitation reconstruction skill is used for a simplistic normal forecast. Further, two additional precipitation scenarios are simulated by adding respectively one and two standard deviations of precipitation to the normal forecast, which is used in probability recovery analysis.

199 Is the NSE performed on the full signals or after removing the climatology sig- nal? It is well known that the climatology will dominate the metric if it is retained. Please clarify. Author's response: Many thanks for the correction, NSE section is removed.

204 In Figure 6, please indicate the regions of weak association. Also, instead of a continuous scale, it would be better to use a discrete scale colorbar, i.e., one colour for a range of values. It is more convenient for the human eye to interpret such images. Author's response: Regions dominated by sub-seasonal signal has a weak association. Modified the figure

265 stimulated –> simulated? Author's response: Corrected 299 "hydrological compartments" – Do you mean storage compartments? Author's response: Modified: hydrological storage compartments

342 "independency from other drought indices" – Do you mean to say that SPI depends on other drought indices? Please clarify the "independence" argument. Author's response: Modified: The GRACE-based drought index is independent of the

meteorological estimates and their combined uncertainties

343 "spatial coverage" – Indices based on NDVI also cover much of the globe. How is this an advantage specific to the GRACE method? Author's response: Modified: The GRACE-based drought index is independent of the meteorological estimates and their combined uncertainties Apart from the specific comments, I would like to indicate that it was rather frustrating to read such a methodology-heavy manuscript devoid of any equations. Even if the equations involved are simple and straight-forward I believe they will provide clarity for the reader. Please consider incorporating equations.

Author's response: Equation and its description added " 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 is the monthly precipitation (P, mm/month); evapotranspiration (ET, mm/month) and 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. "

Your results largely fall into the sequential and diverging types of data for which colorbrewer2.org provides very good advice on choosing colorbars. Typically, sequential data require only one colour with varying intensity to indicate the sequences and diverging data requires two colours of varying intensities. Furthermore, the standard colorbars are not color-blind friendly. I strongly recommend that you follow the rules indicated in the website to improve the graphics in the manuscript.

Author's response: All of the maps are modified with new color bars, please check the attachment.

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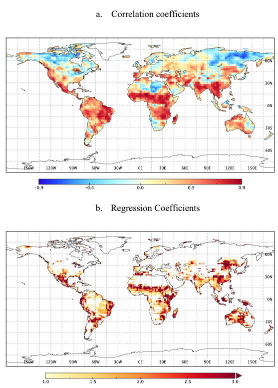

Figure 2: a) Correlation coefficients and, b) regression coefficients between cumulative detrended precipitation anomalies (cdPA) and detrended terrestrial water storage anomaly (dTWSA).

Fig. 1. figure2

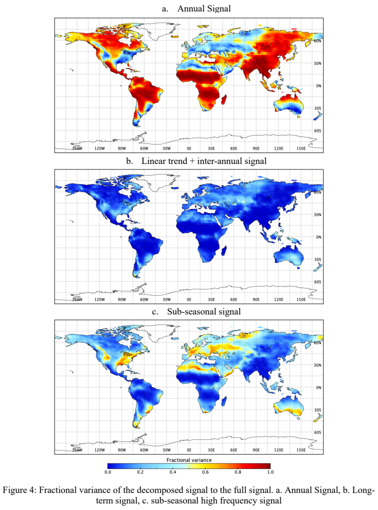

Fig. 2. figure3

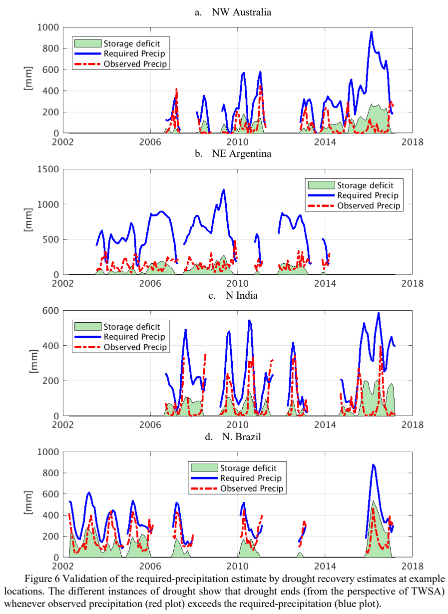

Fig. 3. figure6

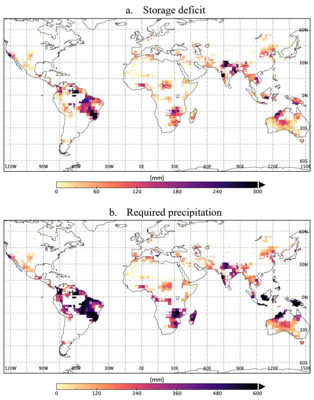

Figure 7: a) Storage deficit in an example month (January 2016). b) the amount of required-precipitation to fill the deficit.

Fig. 4. figure7

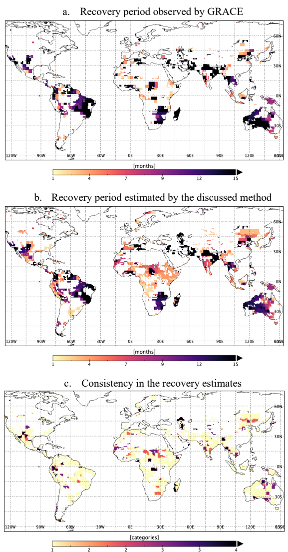

Figure 8: Validation of the estimated required-precipitation by the recovery duration from January 2016 drought observed from: a) GRACE and b) estimated by the discussed method using GRACE and GPCP observations (middle panel). c) consistency in the observed recovery duration by GRACE and GPCP (1 = 1-2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

Fig. 5. figure8

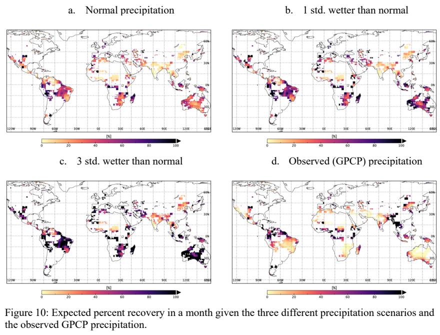

Fig. 6. figure9

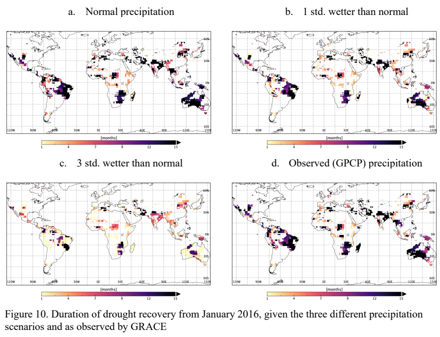

Fig. 7. figure10