Interactive comment on "The El Niño event of 2015–16: Climate anomalies and their impact on groundwater resources in East and Southern Africa" by Seshagiri Rao Kolusu et al. https://www.hydrol-earth-syst-sci-discuss.net/hess-2018-516/

Reviewers' comments in BLACK
Our responses to comments in BLUE (italics are quotes from the paper)

Reply to Anonymous Referee 1:

We would like to thank the reviewer for taking time to review this manuscript thoroughly and for their comprehensive comments received. We have addressed all comments in turn below: We have made all suggested changes in the revised MS.
(Please see them in blue color text)

This paper compares a leading agro climatic indicator (the SPEI) with other estimates of water availability, over two regions of Africa and specifically focusing on the 2015-16 Southern Africa drought. Overall I found this paper to be very well-written and focused, and using some interesting analysis and data products to characterize the 2015-16 season. I especially liked the use of the IAF curves. I recommend this article for publication.

We thank the reviewer for his/her positive comment and finding our study very interesting.

I have two minor points that I think would help the paper, but I will leave it to the discretion of the authors how to respond to these issues.

First, there are many potential data inputs which could be used for the calculation of SPEI. While these are mentioned in the S2 supplemental material, I think that the manuscript would benefit from moving the first paragraph of the S2 section to the manuscript proper. Stating upfront which precipitation and PET estimates are used will help the manuscript by letting people better understand the historical record being used and the flavor(s) of PET calculation.

We understand the reviewer's comment here. The main paper was deliberately written to be as short as possible, with much of the detail in the supplementary material (SM), increasingly popular in many journals. Of course there is a trade-off between brevity and detail in the main paper. Given this comment and comment 1 of reviewer 2 and comment 2 of reviewer 3 we agree that the methods section should include more detail, and have accordingly moved important components from the SM to the main methods section, as advised.

Secondly, I think the identification of the discrepancies between the GRACE data and the SPEI and GLDAS is quite interesting. While this paper is not meant to be a criticism of those other products, I think it should be noted that they are dramatically different in some locations, and that (typically) the GRACE does not match up with the SPEI. I think if this paper is proposing to use the SPEI to characterize drought events that this might be a useful opportunity to clarify these discrepancies, and where to put the confidence. This is touched on in the closing of section 3.2.2, by comparing to the piezometry, but I think that this is an important and relevant finding of this paper, and definitely calls into question the use of GRACE for monitoring groundwater.

We agree that the comparison of the SPEI values with GRACE water storage components (and the contributing GLDAS water budget components) is interesting. Indeed our analysis of the structure of apparent qualitative agreement and discrepancy forms Section 3.2.1 in its entirety. We made informed speculation about the potential sources of the discrepancies, supported by our comprehensive analysis of the uncertainties in the estimation of all the quantities considered. To this we have now added additional clarify on the nature of potential errors in GRACE retrievals of dTWS and cite the most recent approaches to address this. Further, as the reviewer notes our comparison of GRACE dGWS with piezometric observations in Section 3.2.2 provides further insight into GRACE TWS errors (see a new plot, Figure S3, in the supplementary material showing individual TWS time-series data from 3 GRACE solutions). We return to the issue in the Conclusion (lines 526-542) and have now strengthened our cautionary inference as suggested by the reviews (line 540-42).

Interactive comment on "The El Niño event of 2015–16: Climate anomalies and their impact on groundwater resources in East and Southern Africa" by Seshagiri Rao Kolusu et al.

Anonymous Referee #2

Reply to Anonymous Referee 2:

Overall review

This paper by Kolusu et al. examines different climate and groundwater anomalies in East and Southern Africa related to the period of 2015-2016, which corresponded with one of the worst droughts that occurred in Southern Africa. This study puts in context what were some of the major factors leading up to and affecting the severe drought in Southern Africa and the rainy conditions in East Africa, during this period. The paper overall contributes relevant science questions and results, within the scope of HESS, and presents relevant results that address a key water resource issue (i.e., groundwater depletion and recharge) in a vulnerable climate changing region. Major conclusions are reached in this work, but there are some points that the authors may want to consider addressing in their results and discussion. Some examples are provided below in the "Specific comments" section. The abstract and overall presentation of the paper is clear, however, having so much of the background material in the Supplementary Information document requires the readers to continuously refer to the separate document, interrupting the flow of reading the main manuscript at times. Scientific methods and assumptions are outlined and described well, in both the manuscript and Supplementary Information. The results are overall sufficient to support the authors' conclusions, and most of the dataset and method descriptions are well explained. Also, proper credit is given to previous studies and data providers.

Specific comments 1. The authors place much of the paper's background and details in the Supplementary Information section. At times, placing some of the information in the main manuscript would actually help the flow of the paper more, instead of the reader having to constantly refer to the supplementary material. Some examples include the background discussion of the SPEI, which almost all is placed in the Supplementary Information section. However, the SPEI is one of the more crucial metrics used to address their science question on the relationship to the groundwater datasets and anomalies.

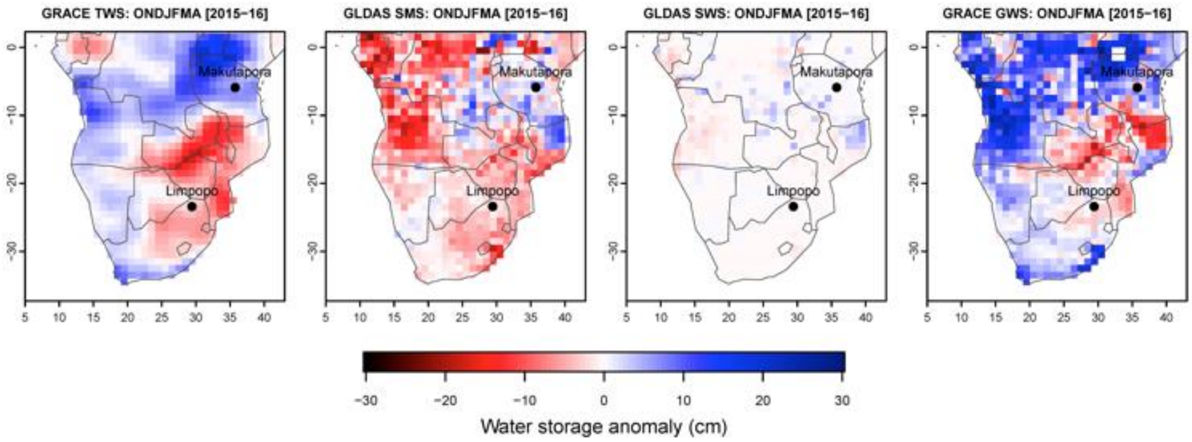
We agree (as does reviewer #1) and have now moved much of the important detail from the Supplementary Information to the Methods section [see lines - 116-168 and 172-241 in the revised manuscript].

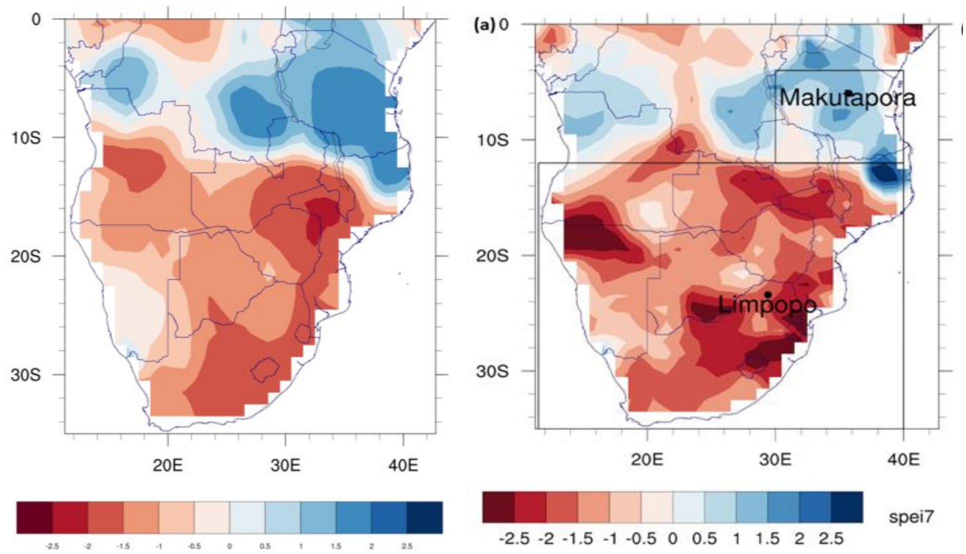
2. Lines 230-233: Authors may want to be careful in stating with such certainty that the "2015-2016 magnitude of the SPEI-7 drought over SA . . . increased two times due to the effects purely of anthropogenic warming. . .". Though anthropogenic warming may be contributing to greater magnitudes, expressed with such drought metrics, other effects such as persistent drought or dry-land-atmospheric feedbacks could have greatly contributed as well.

We agree that attribution of changing climate risks is challenging. For that reason we consider only the contribution of anthropogenic changes in regional temperature to drought risk, for which we have much greater confidence in attribution than we do for anthropogenic influence on regional rainfall (Bindoff et al. 2013). We hope this is clearly explained in both the description of the attribution method (SM Section S2) and in the results section i.e. '*We estimate that the risk of a 2015-16 magnitude SPEI-7 drought over SA to have increased by approximately two times due to the effects purely of anthropogenic warming, ignoring changes to other climate variables and variability*' (lines 324-6). The role of dryland-atmosphere interaction is to some extent accounted for in our method, since the magnitude of the estimated anthropogenic effect on temperature trends (which drives the SPEI) includes those effects at least as simulated in the climate models. We feel that the greatest uncertainties are likely to be associated with the estimation of the return period values for extreme events and we have now strengthened the caveats around our estimate in Section S2.

3. Lines 259-291: The authors report that there are discrepancies between the groundwater water storage (GWS) estimates, involving their three-member GRACE dataset ensemble mean and with the ensemble of SPEI-7 datasets, in both meteorological fields and PET methodologies (e.g., Penman-Monteith vs. Thornthwaite). The question comes up about the different datasets that are used in the SPEI metric methods, i.e., GPCP and CRUTS3.24.01, and different water storage term ensembles, using GLDAS inputs, which use different meteorological datasets, e.g., the GDAS and CMAP-based forcings. Could these factor into the differences seen between the SPEI anomalies and deltaSMS and deltaGWS anomalies? Also, the SPEI is derived based on the data record from 1901 to present, which would be a different period from the GRACE measurements (2002-2016) and then again for the GLDAS datasets (2000-present, if using GDAS). Authors may want to address these possible discrepancies as well.

The reviewer raises a similar point to the first comment of reviewer 1 and we refer to our response to that. In specific response to the query about the potential difference between SPEI-7 derived from GPCC vs CMAP data we have now done that comparison (see below) and note that our the pattern of inconsistency between SPEI-7 and GRACE remains, which we consider in Section 3.2.1. The issue of the differing relative magnitudes of SPEI-7 and TWS anomalies over South Africa is less apparent with SPEI-7(CMAP) and we note that in point (i) in para 2 of Section 3.2.1 (lines 389-391)





Finally, in relation to their results and discussion on this topic, the authors may want to consider that the time windows relevant to the SPEI fields and those of GRACE, and other LSM-based fields, can be different and that the recharge or other drawdowns of groundwater can vary and take time in response to the rainy season. The authors point out this lag in lines 304-306 in relation to figure 5. The October-April SPEI timeframe may not have exactly aligned with the GRACE-ensemble (e.g., deltaTWS) and LSM ensemble (e.g., deltaSMS), as the response to the lower layers may be better reflected in a lagged timeframe (e.g., December-June). Also, trends in the TWS may already have been present that the SPEI-7 may not have captured, given the differences in datasets. Authors may want to look at other studies that have addressed such issues, such as Hassan and Jin (2016), Rodell et al. (2018), and Zhao et al., 2017:

We note this point now in Section 3.1.2 (lines 385-390) and cite the suggested references.

4. Lines 323-325: The authors mention here that the GRACE ensemble-based deltaGWS in the early part of the 2015-2016 drought had a high amount of uncertainty and did not correspond well with the piezometry data for the Limpopo site region. It would be of interest here if they could identify which of the three GRACE TWS anomaly products contributed to the higher blue shaded region in the last half of 2015. Note the lower minimum values of the ensemble spread show some steep decline from late 2015 into 2016. Though the authors do point to the Scanlon et al. (2018) study in lines 302-303 of the Supplementary Information document, it would be of interest to the community to know which product contributed to this GWS reduction.

We thank the reviewer for highlighting the uncertainty in GRACE TWS signals for the Limpopo Basin particularly for the period of 2015-16. We did note in the SM that there is some indication from Fig. S2, that during such periods of greatest ΔGWS uncertainty, it is the uncertainty in GRACE ΔTWS that makes most important contribution, rather than uncertainty in the GLDAS components. We have now looked at the individual TWS time-series data for 3 GRACE products of CSR, JPL-Mascon and GRGS (Fig. S3 reproduced below). We confirm that differences among the three GRACE products for the 2015-16 period are substantial. We note that (i) for late 2015 it is the GRGS product which is largely responsible for the poor correspondence between piezometry and the GRACE mean ΔGWS retrieval, as GRGS, unlike the other two products shows a substantial increase in ΔGWS. (ii) During early 2016 it is the JPL-Mascon (MSCN) product that deviates from the other two showing continued negative anomalies whereas both CSR and GRGS feature slightly positive anomalies. We provide this new plot of GRACE TWS time-series data for both Limpopo and Makutapora basins in the revised supplementary material (Fig. S3) and make appropriate reference in the main text of Section 3.2.2 para 3.

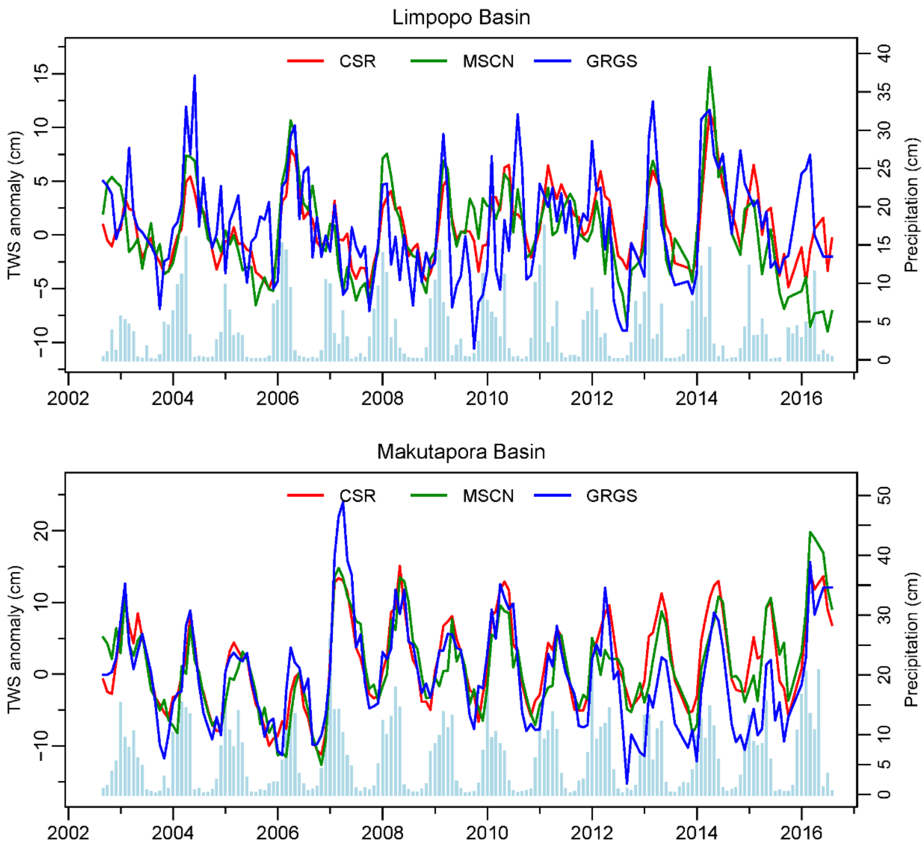


Figure S3: (a) Time series of estimates of monthly ΔTWS anomaly (cm) at Limpopo from August 2002 to July 2016 (averaged over an area approximately ~120 000 km^2) derived from the three individual GRACE retrievals of CSR (red), JPL-Mascons (green) and GRGS (blue). Monthly rainfall (from GPCP product, cm) shown as bars. (b) As (a) but for Makutapora.

Technical corrections Main manuscript: 1. Lines 96 and 111: Noticed that authors use "EASA" instead of "EASE" for the northern of the two domains in these two lines. They should be replaced with "EASE"?

Corrected

2. Line 161: Should the reference to "figure S1(b)" actually be to "figure S1(d)", if highlighting the SST anomalies associated with this 7-month period?

Corrected

3. Line 217: Authors may want to replace the article "an" in front of "East Pacific" with either "than" or "in" here.

Corrected

4. Lines 221-222: The last phrase of this sentence is not fully clear: "and statistically this 2-year drought event remarkably unlikely". Please clarify what is meant here.

The return period estimates for a consecutive 2-year SPEI-7 IAF curves for 2014-16 are extremely high such the uncertainty is too poorly constrained to have confidence. So we prefer not to provide the absolute values

5. Line 315: Remove the comma after "GWS" and before "suggests".

Corrected

6. Lines 341-344: This sentence is a bit awkward in places, e.g., "The magnitude of major GRACE increases in deltaGWS", or "with no response apparent in piezometry." It is recommended to improve these phrases and overall clarity of the sentence.

Corrected

7. Lines 358-362: This is a long run-on sentence, and it is recommended to break this sentence in to two separate ones to improve its readability.

Corrected

8. Line 404: Place the period after the "l" in "et al., 2018).

Corrected

9. Figure 1b: It is unclear about how the 80th percentile of the rainfall anomalies is established. Is this constructed relative to the EASE box? Please clarify further how the positive and negative anomalies are established in Figure 1b (in the main text) relative to the 80th percentile.

This is now explained in the methods section

10. Figure 3 caption, line 619: "men" should be changed to "mean".

Corrected

Supplementary manuscript:

1. Line 107: "EASA" occurs here as well.

Corrected

2. Line 116: "Penman-Montieth" should be spelled: "Penman-Monteith".
Corrected

3. Line 124: Can remove either "use" or "derive" in front of "percentiles".

Corrected

4. Line 125: The authors may want to provide the full name for TRMM 3B42 product, not just the acronym for the satellite and precipitation product. Also, it may be helpful to specify here which years of the TRMM product were used.

Corrected

5. Caption for Figure S1: The final sentence description for S1-d seems incomplete. What period was the anomalies derived from?

Information provided

6. Figure S2a, for Limpopo location, the shading in the top four panels is missing, unlike that for S2b, which shows the shading in those panels for Makutapora. Also, recommend placing the word "and" between "(a) Limpopo" and "(b) Makutapora".

Shading is included in both (a) and (b).

Anonymous Referee #3

Overall its a good paper. I am happy that they treated the 2015-16 drought in context of the dryness of the previous year, this was one of the points I was looking for.

We thank the reviewer for his/her positive assessment.

1. However, given one of their introductory lines: "Few studies have investigated the hydrological impacts of ENSO events on groundwater despite its vital role in sustaining ecosystem function as well as agricultural and domestic water supplies" (line 60-62), I thought they would proceed to do that very investigation which as they mentioned is lacking. I think this statement (line 60-62) should either be removed, or they should explicitly mention that they also do not do this investigation.

Statement now removed as advised

2. Also, a brief background on how the GRACE estimates are derived would be helpful for C1 the readers who are less knowledgeable on climate issues, as this paper could have considerable interest from hydrologists

We agree and not similar comments from reviewers 1 and 2. Accordingly We have now moved the description of the methodology to retrieve GWS from GRACE data from the supplementary material to the methods section of the manuscript (Section 2.2)

3. Line 59: Are not other phenomenon like QBO, MJO etc also major drivers. The way it is written suggest ENSO is the only major driver. Line 65: "strongest" rather than "biggest", perhaps?

We have now clarified this statement and referred directly to section S1 of the supplementary material in which we discuss the various major modes of variability across our study domain (see lines 60-61 and 68)

4. Line 91: "temporally", rather than "temporarily"?

Corrected as suggested

5. Line 221-222: the grammar needs to be corrected, perhaps: "this 2 year drought event [is] remarkably unlikely" (ie, add the word: "is")

Corrected as suggested

6. Line 315-316: It is not clear whether the r of 0.62 is for annual or seasonal? It may be instructive to calculate separate r values for Makutapora and Limpopo, since they are dealing with only 2 sites. Scatter plots would also be a helpful addition.

Clarified as suggested in lines 429-430 and 464. In order to limit the number of Figures we prefer not to show the scatterplots

7. Line 319: remove the word "least"?

Corrected as suggested

8. Line 328-329: the phrase "shows little interannual variability" should perhaps be replaced by "shows a limited interannual cyclicity"

Revised

9. Line 339: The colour scheme on Figure S1 d is a little unusual, in most color schemes red is warmer and blue is colder, this can confuse readers.

Corrected as suggested

10. Line 387-388 need to be revised gramatically.

Corrected as suggested

11. Line 402-403: further analysis is required to support this sentence: "although as our results at Limpopo show, consecutive dry years lead to marked storage reduction"; this can be achieved by for example, by comparing with the storage after another dry year that was in contrast preceded by wet conditions.

We believe that it is clear from Figure 5 that the very weak recharge during 2014-15 and 2015-16 leads to the lowest GWS values on record.

12. Line 420-432: A mention of the use of seasonal climate forecasts along with climate drivers would be helpful, as these seasonal forecast tend to try to bring together the effects of various parameters including climate modes like ENSO, IOD etc.(such forecasts as the ones here: http://www.cpc.ncep.noaa.gov/products/international/nmme/nmme_seasonal_body.html)

This is a good point and we have now included this suggestion. (lines 535-536)

13. Line 639; Fig 5b and 5c. The authors can potentially answer the question of whether GRACE GWS better estimates abstraction rates + borehole GWS by adding the two

We welcome this constructive suggestion to better compare borehole GWS to GRACE GWS. There is one important confounding factor that inhibits the success of implementing this straight-forward suggestion: transience in the response of groundwater levels (i.e. groundwater storage) to changes in pumping from the Makutapora Wellfield. Co-authors Seddon, Taylor and Cuthbert have been working on the development of a numerical model to better represent transience in groundwater-level responses and thus produce a time series record of groundwater levels for the Makutapora Wellfield in which the impacts of pumping have been removed. This work is on-going and they hope to report soon on their results. We will thus leave the observed, uncorrected groundwater-level time series in Figure 5 as it is with all of the associated commentary on the observed impacts of pumping on this groundwater-level record.

The El Niño event of 2015-16: Climate anomalies and their impact on groundwater resources in East and Southern Africa

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Keywords

El Nino; ENSO; Climate; groundwater; Africa; sustainability; recharge; climate impacts; water management; GRACE

Abstract

The impact of climate variability on groundwater storage has received limited attention despite widespread dependence on groundwater as a resource for drinking water, agriculture and industry. Here, we assess the climate anomalies that occurred over Southern Africa (SA) and East Africa, south of the equator (EASE), during the major El Niño event of 2015-16, and their associated impacts on groundwater storage, across scales, through analysis of in situ groundwater piezometry and GRACE satellite data. At the continental scale, the El Niño of 2015-16 was associated with a pronounced dipole of opposing rainfall anomalies over EASE and Southern Africa, north/south of ~12^0S, a characteristic pattern of ENSO. Over Southern Africa the most intense drought event in the historical record occurred, based on an analysis of the cross-scale areal intensity of surface water balance anomalies (as represented by the Standardised Precipitation-Evapotranspiration Index, SPEI), with an estimated return period of at least 200 years and a best estimate of 260 years. Climate risks are changing and we estimate that anthropogenic warming only (ignoring changes to other climate variables e.g. precipitation) has approximately doubled the risk of such an extreme SPEI drought event. These surface water balance deficits suppressed groundwater recharge, leading to a substantial groundwater storage decline indicated by both GRACE satellite and piezometric data in the Limpopo basin. Conversely, over EASE during the 2015-16 El Niño event, anomalously wet conditions were observed with an estimated return period of ~10 years, likely moderated by the absence of a strongly positive Indian Ocean Zonal Mode phase. The strong but not extreme rainy season increased groundwater storage as shown by satellite GRACE data and rising groundwater levels observed at a site in central Tanzania. We note substantial uncertainties in separating groundwater from total water storage in GRACE data and show that consistency between GRACE and piezometric estimates of groundwater storage is apparent when spatial averaging scales are comparable. These results have implications for sustainable and climate-resilient groundwater resource management, including the potential for adaptive strategies, such as managed aquifer recharge during episodic recharge events.

1. Introduction

The El Niño-Southern Oscillation (ENSO) phenomenon is the dominant single driver of interannual climate variability and large-scale extremes across the tropics including much of Africa. Few studies have investigated the hydrological impacts of ENSO events on groundwater. Here, we quantify climate anomalies and groundwater resources over Eastern Africa, South of the Equator (EASE) and Southern Africa (SA), during the recent major El Niño event of 2015-16, which in the Pacific sector was one of the strongest on record. El Niño is typically associated with wet and dry anomalies over EASE and SA, respectively (Ropelowski and Halpert, 1987), but with considerable diversity in this response among El Niño events, in part related to the many other drivers of variability active over EASE and SA (Supplementary Information S1). Much of SA experienced extreme drought in 2015-16 with severe impacts on local food security, livelihoods and key sectors of the economy (SADC 2016a; 2016b; Archer *et al.*, 2017; Siderius *et al.*, 2018; Supplementary Information S1).

Groundwater is the dominant source of safe water for rural populations and many expanding cities in EASE and SA (MacDonald *et al.*, 2012); in drylands, groundwater is often the only perennial source of water. Although relatively under-developed to date, groundwater resources are being developed rapidly in Africa (Taylor *et al.*, 2009; Calow *et al.*, 2010; Villholth *et al.*, 2013) and feature prominently in national development plans, especially to satisfy the need for increased access to safe water and agricultural intensification under rapidly growing populations and economic development. Groundwater is especially important in Africa where surface runoff efficiency is lower than elsewhere (McMahon *et al.*, 1987) and drinking of untreated surface water is associated with poor health (Hunter *et al.*, 2010). The long-term viability of groundwater withdrawals and the livelihoods and ecosystems that groundwater sustains depend on recharge.

Unlike surface water, research evaluating associations between groundwater storage and ENSO, or indeed other modes of climate variability is rather limited (e.g. Holman *et al*., 2011, Kuss and Gurdak, 2014), despite evidence that climate variability and extreme rainfall preferentially drive or restrict groundwater recharge. Several studies have shown recharge to be episodic in semi-arid regions of Africa (Meyer *et al.*, 2005, van Wyk *et al.*, 2011, Taylor *et* *al.*, 2013, Cuthbert *et al.*, 2017) and elsewhere (Jasechko and Taylor, 2015, Cuthbert *et al.*, 2016), highlighting the need to understand patterns and drivers of climate variability both temporally and spatially, that influence recharge. Bonsor et al. (2018) analysed recent (2002-2016) trends in, and seasonality of groundwater storage within 12 African sedimentary basins implied from GRACE satellite data. Here, we employ evidence from both in situ observations (piezometry) and GRACE satellite data to examine the effect of large-scale interannual climate anomalies on groundwater across spatial scales for locations and domains that represent the rainfall anomaly gradient over EASE and SA associated with characteristic El Niño response, exemplified by the event of 2015-16. Beyond a few site-specific studies, the impacts of larger-scale climate extremes on groundwater remain substantially unresolved. This hinders our ability to determine acceptable levels of groundwater abstraction and depletion. This study aims to quantify and understand the responses, during the 2015-16 El Niño of (i) the surface/terrestrial water balance and (ii) groundwater storage over EASE and SA from regional to local scales. Further, it seeks to place the 2015-16 El Niño event statistically in the historical context.

2. Data and methods

2.1. Climate data and analysis

We analyse data over the broad region of Africa South of the Equator and over an extended austral summer wet season of October-April, which encompasses the full wet season over SA (excluding the Cape region) and those parts of EASE (south of ~5°S), which experience a similarly annual unimodal rainfall regime (Dunning *et al.*, 2016), and will accommodate the response time of groundwater systems to climate. This region also experiences a coherent ENSO signal (Section 3.1).

We use the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano *et al.*, 2010), which is a simple representation of surface water balance anomalies, derived over this 7-month season (SPEI-7), over the period 1901 to present using precipitation data from the Global Precipitation Climatology Centre (GPCC) monthly product v7 (Schneider *et al.*, 2011; 2014) at 1.0° resolution. To account for uncertainty in estimation of PET we use three parameterisations of varying complexity: The Penman-Monteith equation, based on net radiation, temperature, wind-speed and vapour pressure); The Hargreaves equation, based on mean, minimum and maximum temperature and extra-terrestrial solar radiation; The Thornthwaite equation, which is based solely on surface air temperature. The variables required for the various PET estimates are obtained from the CRUTS3.24.01 dataset (Harris *et al.,* 2014). Note that some findings will be sensitive to this choice of drought index.

SPEI-7 anomalies are analysed for two large sub-domains, specifically EASE (4-12°S, 30-40°E) and SA (10-35°S, 10-40°E) which encompass the anomalous wet and dry dipole conditions, respectively, typically experienced during El Niño events (Fig. S1(b)) and specifically in 2015-16 (Fig. 1(a)). For each domain, the areal extent and intensity of SPEI-7 in each year of the record was characterised using Intensity-Areal-extent Frequency (IAF) curves of Mishra and Cherkauer (2010). IAF curves show the mean SPEI-7 value of grid cells lying within various areal extent intervals: The areas covered by the lowest (for SA) or highest (for EASE) 5th, 10th, 20th…100th areal percentiles of SPEI-7 grid cell values within the domain area i.e. when all grid cells are ranked. The SPEI-7 IAF curves allow comparison between years, irrespective of the precise spatial location of dry/wet anomalies within the domain. This comparison includes estimating the return period of the SPEI-7 IAF curve observed during the 2015-16 El Niño and other El Niño events. This is achieved by comparing these observed SPEI-7 IAF curves to curves representing various benchmark return periods, derived using a block maximum method applied to SPEI-7 data from a large ensemble of climate model runs (see Supplementary Information S2).

It is likely that anthropogenic climate change is, and will continue to, affect large-scale hydrology (Bindoff *et al.,* 2013). Here we estimate the effects purely of anthropogenic temperature trends on drought risk over SA through a simplified attribution experiment. The SPEI-7 IAF return period analysis above is repeated, but with respect to benchmark return period IAF curves for which the temperature data, used in calculating PET, has the signal of anthropogenic climate change removed (see Supplementary Information S2). As such, the return period of the SPEI-7 IAF curve for 2015-16 is estimated in the context of the 'real historical' world and for comparison in the context of a counterfactual climate with only natural variability in temperature.

There is evidence to indicate recharge is preferentially driven by intense rainfall (see references in Sections 1 and 3.1.1). To examine the nature of rainfall intensities over EASE during the El Niño 2015-16 event we derive percentiles of the daily rainfall probability distribution from the Tropical Rainfall Monitoring Mission (TRMM) 3B42 product during the (October-April season, 1997-2016). In the absence of robust knowledge of actual rainfall thresholds associated with groundwater recharge, and the likelihood that such thresholds are highly variable in space and time, we derive the 80th percentile of daily rainfall within the season, at each grid cell as a coarse proxy for rainfall events likely to be associated with recharge. Our results (Section 3.1.1) are largely insensitive to the choice of percentile value (not shown). We derived the value of the 80th percentile from all the (October-April) data and then just for the 2015-16 season and show the anomalies. Finally, Information on the large-scale atmospheric circulation is diagnosed from the horizontal and vertical winds, and specific humidity from ERA-Interim reanalysis data (Dee *et al.*, 2011). SST data are obtained from the extended reconstructed sea surface temperature (ERSST) version 4 from the National Oceanographic and Atmospheric Administration (NOAA) (Smith *et al.*, 2008) on a 2° grid.

<u>2.2 Groundwater storage estimates from GRACE satellite data</u>

Regional-scale changes in groundwater storage (GWS) (2002-16) are estimated from GRACE satellite measurements of total terrestrial water storage (TWS) anomalies, by subtracting changes in the other terrestrial stores, which, in our tropical region, comprise soil moisture (SMS) and surface water (SWS) stores (eq.1), themselves estimated from Land-Surface Model (LSM) simulations, in the absence of in situ ΔSMS and ΔSWS data in the study areas.

$$\Delta GWS = \Delta TWS - (\Delta SMS + \Delta SWS) \qquad \text{(eq. 1)}$$

Where Δ refers to the anomaly with respect to the long-term data series. To help interpretation of the mean ΔGWS signals we also present the total uncertainty in estimates of ΔGWS, which results from the uncertainty in estimates of ΔTWS, ΔSMS and ΔSWS. Regarding uncertainty in ΔTWS associated with different GRACE processing strategies, we apply an ensemble mean of three GRACE ΔTWS estimates. Namely, the CSR land (version RL05.DSTvSCS1409, Swenson and Wahr, 2006; Landerer and Swenson ,2012) and JPL Global Mascon (version

RL05M_1.MSCNv01, Watkins *et al.*, 2015; Wiese *et al.*, 2015) solutions, from NASA's *GRCTellus* data dissemination site (http://grace.jpl.nasa.gov/data), and a third GRGS GRACE solution (CNES/GRGS release RL03-v1) (Biancale *et al.*, 2006) from the French Government space agency, Centre National D'études Spatiales (CNES). Further information on the processing involved in each product is provided in Supplementary Information S3. The monthly GRACE ΔTWS are interpolated to a 1-degree grid for analysis in Equation 1. For analysis of GRACE ΔTWS data at the locations of the two groundwater-level monitoring sites of interest (Makutapora and Limpopo, see below) the monthly ΔTWS time-series are generated by averaging over a 200 km radial buffer (i.e. area equivalent of ~120 000 km^2) around each location.

Further, to account for uncertainty in ΔSMS and ΔSWS we use data from four LSMs within NASA's Global Land Data Assimilation System (GLDAS), and provide the associated uncertainty ranges for each term. GLDAS is an uncoupled land surface modelling system that includes multiple global LSMs driven by surface meteorology from the NCEP data assimilation system, CMAP disaggregated precipitation and the Air Force Weather Agency satellite-derived radiation fields (Rodell *et al.*, 2004). The four GLDAS LSMs are: The Community Land Model (CLM, version 2) (Dai *et al.*, 2003), NOAH (version 2.7.1) (Ek *et al.*, 2003), the Variable Infiltration Capacity (VIC) model (version 1.0) (Liang *et al.*, 2003), and MOSAIC Mosaic (version 1.0) (Koster and Suarez, 1992). Further discussion of the uncertainty in these individual water balance components (Fig. S2) and further information on the LSMs is provided in Supplementary Information S3.

2.3 Groundwater storage estimates from piezometric observations

Groundwater-level time series records were compiled in two areas situated at the heart of the EASE/SA ENSO rainfall dipole centres of action (Fig. 1(a)). (i) The Makutapora wellfield (35.75°E, 5.90°S) site in central Tanzania, East Africa. Groundwater records were collated from the Ministry of Water and Irrigation and the Dodoma Urban Water Supply, Tanzania. Here, groundwater is abstracted from an aquifer comprising deeply weathered granite overlain by alluvium (Taylor *et al.*, 2013). Data from three sites in the wellfield met the data quality criteria and are averaged together; mean groundwater-level time series records were converted to monthly anomalies in GWS using an in-situ derived specific yield (S_y) value of 0.06 (Taylor *et al.*, 2013). We estimate that these data are representative of groundwater levels across an area of ~60 km^2. (ii) Limpopo Basin in Southern Africa (~28 to 32°E, 22.5 to 25°S). Groundwater-level records from 40 stations within weathered hard-rock ("basement") aquifers in sub-basins A6 (Mogalakwena), A7 (Sand), A8 (Nzhelele) and A9 (Luvuvhu) of the Limpopo Basin were collated from the Department of Water and Sanitation, Directorate Surface and Groundwater Information, South Africa. The data were first standardised then averaged together and represent an area estimated to be ~ 47 000 km^2. For both sites daily to monthly groundwater-level records within our common study period of August 2002 to July 2016, were checked for consistency (missing data less than 10%) and selected for groundwater storage analysis. Mean groundwater-level time series records were converted to monthly anomalies in GWS using a S_y value that produced the lowest root-mean square error between in situ and GRACE GWS; the applied value (0.025) is consistent with that estimated for basement aquifers in Africa by MacDonald *et al.* (2012).

We acknowledge that our estimates of GWS from piezometry may be influenced by abstractions and we provide data on pumping rates from Makutapora (Fig. 5(c)). A numerical method to remove the effects of pumping is currently the subject of ongoing research by the authors, so in this case we infer the effect of pumping on GWS only in only relative qualitative terms. Equivalent direct data on direct pumping rates is not available at Limpopo. However, we note that Cai *et al.* (2017) mapped the spatial extent of irrigation across the Limpopo basin in South African using satellite data and estimated that irrigation from groundwater provides about 50% of the irrigated areas over 2% of the land area, which likely influences groundwater storage locally.

3. Results and discussion

<u>3.1 Climate anomalies over EASE and SA during the 2015-16 El Niño event</u>

3.1.1 EASE/SA climate anomalies

The 2015-16 El Niño was the second strongest event within the available ~165-year Pacific Ocean Sea Surface Temperature (SST) record, with SST anomalies exceeding 2^{o}C for 6 months from October 2015 (Fig. S1(d)). By some measures 2015-16 was the strongest El Niño since 1950 (Supplementary Information S1). Many of the observed climate anomalies around the world were typical of El Niño years (Blunden and Arndt 2016). Over our study region, a pronounced north-south dipole in SPEI-7 anomalies was observed (Fig. 1(a)), indicating intense and extensive drought over SA (negative SPEI-7) and the wetter than normal conditions over EASE (positive SPEI-7). In detail, most of SA south of 10°S experienced a substantial water balance deficit: exceptional drought (SPEI <-2) conditions were experienced over extensive parts of northern South Africa and northern Namibia, southern Botswana and Zambia, as well as most of Zimbabwe and southern Mozambique and Malawi (Fig. 1(a)). Most of EASE experienced above average rainfall during this period, with SPEI values >1 across most of Tanzania, and a localised exceptionally wet region over the northernmost part of Mozambique. The Makutapora and Limpopo sites (Fig. 1(a)) are located in areas representative of the large-scale north/south rainfall dipole.

This spatial dipole pattern is very similar to the characteristic pattern of anomalies during El Niño across the region, as represented by the leading Empirical Orthogonal Function (EOF) of interannual variability (Fig. S1(b), Section S1) which correlates strongly with ENSO and Indian Ocean SSTs Fig. S1(c). Indeed, the EOF coefficient value for 2015-16 is the second highest within the entire 1901-2016 period. As such, across our study region 2015-16 represents an extreme exemplar of the characteristic El Niño climate response. Of course, a complex set of planetary, regional and local scale processes related to, and independent of, El Niño are fully responsible for the observed anomalies (e.g. Blamey *et al*., 2018). The structure of the atmospheric anomalies, specifically the mean meridional overturning circulation associated with the large-scale SPEI-7 anomalies (Fig. 2(a)) shows large-scale anomalous ascent over EASE between ~0^{o} and 10^{o}S indicative of enhanced deep convection, with compensating descent over SA throughout the depth of the troposphere, which acts to suppress convection. The low-level horizontal circulation (Fig. 2(b)) indicates key features associated with the SPEI-7 dipole, notably: (i) An anomalous southerly flow from the southern Indian Ocean into continental SA (Feature A in Fig. 2(b)), which weakens the transport of water vapour from the humid tropical Indian Ocean leading to a decrease in moisture flux convergence over SA. This is associated with a weakening of the mean 'Mascarene' subtropical high over the Southern Indian Ocean (Feature B in Fig. 2(b)). (ii) Over EASE there are anomalous low-level westerlies over Tanzania (Feature C in Fig. 2(b)), which weaken the mean easterlies and enhance convergence over Tanzania, a structure characteristic of wet spells (Berhane and Zaitchik, 2014; Nicholson 2017).

Groundwater recharge in the semi-arid tropics is favoured by high intensity rainfall events (Owor, 2009; Jasechko and Taylor, 2015) within wet seasons, which may be modulated by climate anomalies during El Niño conditions. During 2015-16, the intensities of the 80th percentile of daily rainfall, a simple proxy of potential groundwater recharge-relevant rainfall, increased by ~1-5 mm day^{-1} across much of EASE (Fig. 1(b)), representing a 100-150% increase in many places. Whilst the association of rainfall intensity and enhanced recharge across large and heterogeneous regions remains to be resolved, this intensification of rainfall is consistent with greater groundwater recharge. Across SA the magnitude of the 80th percentile reduced by ~1-2 mm day^{-1}, potentially reducing groundwater recharge.

3.1.2. The 2015-16 event in the historical context

SPEI-7 IAF curves represent water balance anomalies across all spatial scales. For the SA region, 2015/16 experienced the most extreme SPEI-7 drought within the historical period, with an estimated IAF curve return period of ~260 years (range 190-290 years) (Fig. 3(a)). The 2015-16 drought was of greater intensity than those during previous El Niño events of comparable magnitude, 1997-98 and 1982-83, whose SPEI-7 IAF curve return periods are estimated to be only ~6 years (range 4-9 years) and ~43 years (range 35-47 years), respectively). The contrasting intensity of SA drought between these events highlights the diversity in responses over EASE/SA to El Niño, related to both the different character of the events in the Pacific sector (2015-16 was strongest in the central rather than East Pacific as in 1997-98, see Section S1), and the specific regional circulation features during these events which modulate the diverse ENSO teleconnections to SA (Ratnam *et al.*, 2014; Blamey *et al.*, 2018). Moreover, the 2015-16 drought followed a moderate drought in 2014-15 (Blamey *et al.*, 2018), which had important implications for groundwater levels (Section 3.2.2), and statistically this 2-year drought event is remarkably unlikely. The extreme SPEI-7 anomalies over SA in 2015-16 result from low rainfall and extremely high temperatures (Brundel and Arndt, 2016, Russo *et al.*, 2016), potentially related to land-atmosphere feedback processes (e.g. Seneviratne *et al.*, 2010), through reduced vegetation and soil moisture, perhaps persisting from 2014-15. Uncertainty in the strength of land-atmosphere coupling over SA remains high with contradictory results from model analyses (e.g. Koster *et al.*, 2006) and combined observation-model analysis (Ferguson *et al.*, 2012), suggesting weak and strong coupling, respectively. Further, warming across SA in recent decades can be attributed substantially to anthropogenic radiative forcing (Bindoff *et al.*, 2013). As such climate risks are changing. We estimate that the risk of a 2015-16 magnitude SPEI-7 drought over SA to have increased by approximately two times due to the effects purely of anthropogenic warming. Note this estimate does not include any anthropogenic changes in any of the other climate variables which determine SPEI, most notably precipitation, nor changes in variability of climate (see Supplementary Information S2). Further, other drought indices may have differing sensitivities to anthropogenic temperature trends.

Over the EASE domain as a whole, the 2015-16 event was wet but not extreme, with an SPEI-7 IAF curve estimated return period (Fig. 3(b)) of only ~10 years (range 5-12 years). The anomalies were far weaker than that during the 1997-98 El Niño (Fig. 3b). These differences may be associated with the state of the Indian Ocean Zonal Model (IOZM), an east-west structure of coupled ocean-atmosphere circulation, influencing convection and rainfall over East Africa (Saji *et al.*, 1999, Supplementary Information S1). The 1997-98 El Niño coincided with a very strong positive IOZM event, unlike that of 2015-16, in which the IOZM was weakly positive. Indeed, the wettest EASE year on record, 1961-1962, experienced a very strongly positive IOZM event but no El Niño event (Nicholson, 2015).

3.2 Impact of 2015-16 climate anomalies on groundwater storage

3.2.1 Large-scale estimates of ΔTWS, ΔSMS, ΔSWS and ΔGWS

Regionally, GRACE ensemble-mean ΔTWS anomalies (Fig. 4(a)), and estimated ΔGWS (eq. 1, Fig. 4(d)), for 2015-16 reflect the north-south dipole over EASE/SA associated with the El Niño-related SPEI-7 climate anomalies (Fig. 1(a)). Positive ΔTWS and ΔGWS anomalies exist north of ~10°S across EASE (including the Makutapora site), the central DRC and northern Angola. Negative ΔTWS and ΔGWS anomalies occur over an extensive region of eastern SA including the Limpopo site. However, despite broad-scale structural similarity, there are some apparent inconsistencies between ΔTWS (and other components of the water budget, including ΔGWS) and the SPEI-7 climate signal that we consider below.

Viewed more closely, the partitioning of large-scale ΔTWS anomalies between the modelled ΔSMS, ΔSWS and residual ΔGWS is spatially complex. First, we note that ΔSWS (Fig. 4(c)) plays only a minor role across the domain. Further, the coherence of the spatial structure in anomalies in ΔSMS (Fig. 4(b)) is much less clear than for ΔTWS, reflecting uncertainties in soil moisture among individual LSMs, as highlighted by Scanlon *et al.* (2018). Then, considering the drought region over SA, a number of features emerge. (i) The relative magnitude of ΔTWS deficits over South Africa are less than those of the SPEI-7, compared to the northern more humid parts of SA (compare Fig.s 4(a) and 1(a)). This difference may be expected since ΔTWS is an absolute measure of water volume whereas SPEI-7 is a standardised anomaly relative to climate, derived over a much longer time period from a different rainfall data than that used in the GLDAS system. Consequently, these measures may be expected to diverge across mean rainfall gradients. Further, SPEI-7 reflects potential rather than actual evapotranspiration. (ii) Over the northern sector of Zambia, Zimbabwe and Malawi the strongly negative ΔTWS anomaly is almost equally shared between modelled reductions in ΔSMS and ΔGWS. (iii) To the south over South Africa however, the (rather weaker) ΔTWS deficits are effectively accounted for by ΔSMS anomalies such that ΔGWS anomalies are actually close to zero or indeed slightly positive. The Limpopo study site lies at a transition zone between regions with apparently strongly reduced ΔGWS to the northeast and close to zero or slightly positive ΔGWS to the southwest. As geology is broadly continuous across the region, the transition is largely related to uncertainty in the estimation of modelled ΔSMS.

Further, considering the anomalous wet region over EASE to the north of ~10°S, ΔGWS broadly mirrors the structure of ΔTWS, but the detailed picture is complex. Over most of Tanzania and Angola positive ΔTWS anomalies are largely partitioned into the ΔGWS rather than ΔSMS, whereas over southern DRC the reverse is the case. Moreover, there are interesting apparent contradictions between the climate SPEI-7 and GRACE ΔTWS data. Over Namibia and southern Angola, negative SPEI-7 (Fig. 1(a) and ΔSMS, Fig. 4(b)) coincides with positive ΔTWS anomalies (Fig. 4(a)) leading to very strong positive ΔGWS anomalies (Fig. 4(d)) that are therefore inconsistent with climate anomalies from SPEI-7. Conversely, and more locally, over northern Mozambique, a positive ΔSMS anomaly, resulting from the driving rainfall data (see the SPEI-7 wet anomaly, Fig. 1(a)) is not reflected in a strong ΔTWS signal, which leaves a counterintuitive, negative residual response in ΔGWS. As such, GRACE ΔGWS exhibits inconsistent responses to both apparent anomalous dry and wet conditions. These are likely to be a result of (i) limitations in observational precipitation data, (ii) uncertainties in GRACE TWS retrievals (as well as unwanted artefacts from surface and tectonic deformation) (iii) uncertainties in estimation the individual components of water storage from LSMs, and (iv) differing timescales of response across the various data. Such issues have been noted and assessed elsewhere (Hassan and Jin, 2016; Zhao *et al.*, 2017; Rodell *et al.*, 2018; Scanlon *et al.*, 2018). Resolving these issues is challenging but recent studies have sought to constrain the uncertainty in the modelled components of water storage through assimilation of GRACE TWS into hydrological models (Khaki *et al.*, 2018; Schumacher *et al.*, 2018).

3.2.2 In situ and GRACE-derived estimates of ΔGWS at the Makutapora and Limpopo Basins

Piezometry for the two observatory sites and changes in GWS estimated from GRACE and LSMs are shown in Fig. 5. First, we note that uncertainty in the mean GRACE ΔGWS estimate (blue shading around blue line in Figs. 5(a) and 5(b)), whilst often large, is generally smaller than the signals of inter-annual variability which are the main focus of our analysis. However, variability in mean GRACE ΔGWS within recharge seasons is small relative to uncertainty, such that we cannot confidently draw inferences at these timescales.

Specifically, at the SA Limpopo site, observed piezometry (Fig. 5(a)) shows an annual cycle in GWS in most years with a 'saw tooth' pattern representing steady recessions in GWS during the dry season from May to October followed by rapid increases typically starting in December in response to the onset of the wet season to peak post-wet season in April (lagging peak rainfall by ~1-2 months). GWS in 2015-16 is well below average with a seasonal but subdued GWS rise delayed (until March) due to the highly anomalous early wet season drought. The GWS rise in March-April following rains in March is the second smallest on record; only 2002-3 has lower seasonal increase in GWS. The 2015-16 drought is preceded by negligible recharge in the dry year of 2014-15 (Fig. 5(a)), such that GWS as of mid-2016 was lowest in the 14-year record. As such, the major drought of 2015-16 compounded weak recharge in the previous year to leave GWS at historically low levels. This may have been compounded by increased abstractions during these dry years.

Comparison of piezometry and GRACE-derived GWS at Limpopo (Fig 5(a)) suggests a broad correspondence when seasonally averaged, ($r = 0.62$, significant at the 0.01 probability level). The prolonged decline over 2014-16 is observed in both GRACE and piezometry. When averaged over all years, the mean annual cycle is similar in phase and magnitude (not shown). As such, at least broad temporal averaging scales GRACE is corroborated by piezometry at the Limpopo site, where the scales of spatial averaging are similar. However, within-seasons, the uncertainty in GRACE ΔGWS leads to a much 'noisier' mean signal at Limpopo which cannot resolve the annual 'saw-tooth' pattern (Fig. 5(a)): in GRACE ΔGWS individual years have a rather variable annual cycle despite a clear cycle in rainfall. Notably, a strong rise in the ensemble mean GRACE ΔGWS during early season 2015-16 is not corroborated by piezometry or rainfall. This period coincides with the greatest uncertainty in GRACE ΔGWS among the three GRACE products (see blue shading around ensemble mean GRACE estimates in Fig 5a). There is some indication from Fig. S2, that during such periods of greatest ΔGWS uncertainty, it is the uncertainty in GRACE ΔTWS that makes most important contribution, rather than uncertainty in the GLDAS components. From the individual GRACE ΔTWS products (Fig. S3) we note that the mean GRACE vs. piezometry ΔGWS discrepancies in late 2015 result largely from the GRGS product, which shows a non-corroborated increase in ΔTWS.

At the EASE Makutapora site, observed piezometric-GWS (Fig. 5(b)) shows little regular inter-annual variability, with long periods of GWS recessions e.g. 2002-6, 2012-16, interrupted by irregular and infrequent GWS increases, in declining order of magnitude 2006-7, 2009-10 and 2015-16, all El Niño years. The wet conditions in 2015-16 produced a major recharge event though observed piezometric responses are smaller than in 2006-7 and 2009-10, despite higher rainfall (Fig. 5(b)). Under highly dynamic pumping regimes (Fig. 5(c)), GWS changes are only a partial proxy for groundwater recharge; the sharp increase (~50%) in wellfield pumping in May 2015 served to diminish the response in piezometric-GWS to the 2015-16 El Niño.

Overall, however, the findings are consistent with the analysis of Taylor *et al.* (2013) who note highly episodic recharge at Makutapora over the period since the 1960s associated with years of heavy rainfall. The 2015-16 El Niño event represents a major event driving GWS at the Makutapora wellfield, despite moderate rainfall anomalies over EASE.

There is only a rather general association between GRACE and piezometric estimates of groundwater storage variability at the Makutapora site. However, the episodic recharge events in the piezometry data of 2006-7, 2009-10 and 2015-16 are matched quite well by the magnitude of major GRACE increases in ΔGWS, although the second largest GRACE ΔGWS increase occurs in 2014-15 with no response apparent in piezometry. Overall, the seasonal correlation of GRACE ΔGWS and piezometric GWS of 0.51 is only moderate (significant at the 0.05 probability level) but clearly reflects the low frequency multi-annual trends (at least up to 2013) as well as interannual variability.

However, stark differences between GRACE and piezometry are apparent. In contrast to piezometry, GRACE (Fig. 5(b)) shows increases in ΔGWS in almost every year (with lag of ~1 month after the rainfall annual peak), suggesting recharge occurs annually, in contrast to the piezometry. Further, GRACE ΔGWS replicates the low frequency recessionary trend over the period 2002-07 but not since 2012. Resolving these contradictions is problematic but two likely explanations emerge (i) Incommensurate scales of observation from piezometry (area ~60 km^2) and GRACE (~200,000 km^2). More localised processes may dominate the piezometry record, perhaps including recharge sensitivity to contributions from local ephemeral river flow and rainfall. Further, the effects of local pumping strongly influence the piezometric record, obscuring recharge events of low magnitude. This could explain the discrepancies in low frequency trends between the GRACE and piezometry. Specifically, the period 2002-07 over the which the data agree reflects a widespread groundwater recession, following the anomalously high recharge during the El Niño event of 1997-98 (Taylor *et al.,* 2013), whilst the recent accelerated recessionary trend since 2012 reflects the effects of a rapid increase in abstraction, which has a more localised effect apparent only in the piezometric observations. As such the piezometric record may only show episodic recharge whilst GRACE may indicate annual and episodic recharge processes. (ii) Errors in GRACE ΔGWS resulting from inaccurate accounting of ΔSMS and ΔSWS, which leaves a residual artefact of an annual positive ΔGWS signal, see Section 3.1, *Shamsudduha et al.* (2017) and Scanlon *et al.* (2018). Such errors may not be adequately accounted for in the uncertainty estimates in GRACE ΔGWS given, for example similarities in LSM design and driving data. Indeed, at both the Limpopo and Makutapora sites, we note stronger correlations between seasonal local rainfall and piezometric GWS than with GRACE ΔGWS (not shown).

4. Concluding Discussion

We quantify the climate anomalies and groundwater response during the major El Niño event of 2015-16, over Southern and Eastern Africa, south of the equator, across a range of spatial scales from regional to local. Our analysis confirms that the event was associated with a pronounced north/south dipole pattern of positive/negative rainfall and water balance anomalies over EASE/SA, typical of the ENSO teleconnection to the region. It was the second largest such dipole event on record since 1900. Considerable diversity nevertheless exists in climate anomalies over Africa between El Niño events.

The response of the water balance including GWS to ENSO is marked. Over EASE, total rainfall and daily intensities were higher than normal and we estimate the return period for the SPEI-7 water balance metric, over the domain as a whole, to be ~10 years. Wet anomalies over EASE were actually moderated by the occurrence of a rather weak IOZM event. Nevertheless, the anomalously wet conditions led to strong groundwater recharge over the EASE domain as evidenced from GRACE. At the Makutapora wellfield in Tanzania, 2015-16 the strong El Niño-related rainfall acted to reverse a long-term decline in observed in-situ groundwater storage associated with a rise in intensive pumping rates. Changes in GWS estimated from an ensemble of GRACE and LSMs also reflect the occurrence of substantial groundwater recharge in 2015-16 and indicate annual groundwater recharge across the region. Broadly, the analysis reinforces the importance of large-scale climate events in driving episodic recharge, critical to replenish heavily exploited aquifers.

Over SA, the 2015-16 El Niño was associated with extreme drought, the strongest within the observed 116-year record, with an estimated return period of ~260 years, resulting from exceptionally low rainfall and high temperatures. The drought resulted in groundwater storage declines through most of the wet season at our Limpopo study site, with strongly reduced recharge experienced, the second lowest on record. Furthermore, this followed a dry year 2014-15 leading to two consecutive years of low recharge and the greatest recession on record. Clearly, groundwater provides a valuable buffer for periods of reduced surface water availability in drought conditions, although as our results at Limpopo show, consecutive dry years lead to marked storage reduction. Climate projections suggest reduced early season rainfall across much of SA (Lazenby *et al.* 2018) compounding rising temperatures, and the implications of this for climate resilience require a better understanding of these impacts on groundwater recharge as well as surface water resources.

GRACE data and LSM outputs are clearly useful in complementing in-situ data, but a number of issues emerge. Although at the broadest scale the GRACE ΔGWS anomalies in 2015-16 are consistent with rainfall anomalies, there are a number of apparent inconsistencies over quite large areas. Resolving the underlying reasons for these is problematic, but likely candidates include the effects of inadequate climate data over Southern Africa, influencing and compounded by uncertainties in ΔSMS and ΔSWS estimates simulated by land surface models, on which the estimation of GRACE ΔGWS depends. When averaged over comparable scales at Limpopo GRACE and piezometry agree well, at least for seasonal averages. Comparison with the local observations shows that GRACE GWS estimates are considerably noisier, especially at Makutapora where the spatial averaging scale of in-situ data and GRACE differ greatly. Local groundwater abstractions are apparent in the Makutapora record and very likely at Limpopo. Our results suggest that further analysis of the robustness of GRACE estimates of GWS is advisable and, as such, these estimates should be treated with considerable caution.

Our results highlight the potential for adaptive strategies, such as managed aquifer recharge, for optimising the capture or storage of episodic recharge in East Africa during El Niño and/or positive IOZM events, and by corollary over Southern Africa during La Niña events (given the opposing dipole structure of ENSO-related rainfall anomalies across SA/EASE). Of course other modes of climate variability driving rainfall extremes are also important. Such interventions can enhance the positive role of groundwater in climate-resilient water and drought management. Seasonal climate prediction may have a potential role to inform such adaptive water management strategies. At Makutapora, managed aquifer recharge exploiting

El Niño and/or positive IOZM events may contribute to resilient urban water supply systems for the city of Dodoma. Our findings strengthen the case for a greater understanding of the drivers of rainfall extremes over Africa and their relationship with recharge processes under past, current and future climates and at various temporal and spatial scales. Such knowledge is crucial to inform water management policies and practices for sustainable and climate resilient development in a region undergoing rapid development of groundwater resources.

Competing Interests. The authors confirm they have no competing interests

Author contribution. SK and MT conceived the paper. Data analysis was conducted by all authors. MT and SK prepared the manuscript with contributions from all co-authors.

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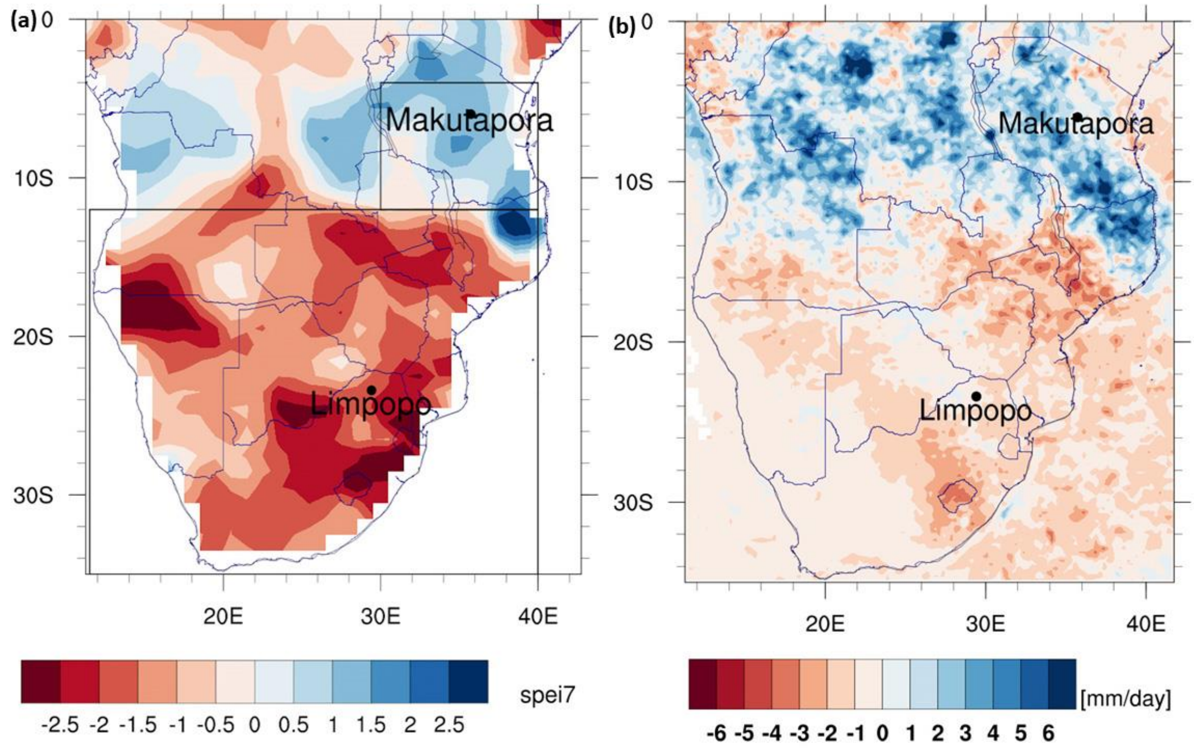

Fig. 1. Large-scale climate anomalies over the study region for October-April 2015-16. (a) SPEI-7 (b) Anomalies of the 80th percentile of daily TRMM rainfall (mm day^{-1}). Boxes in (a) show the EASE (small box) and SA (large box) domains used in the SPEI-7 IAF analysis (see Section 2.1 and S2). The piezometer observation locations are also shown.

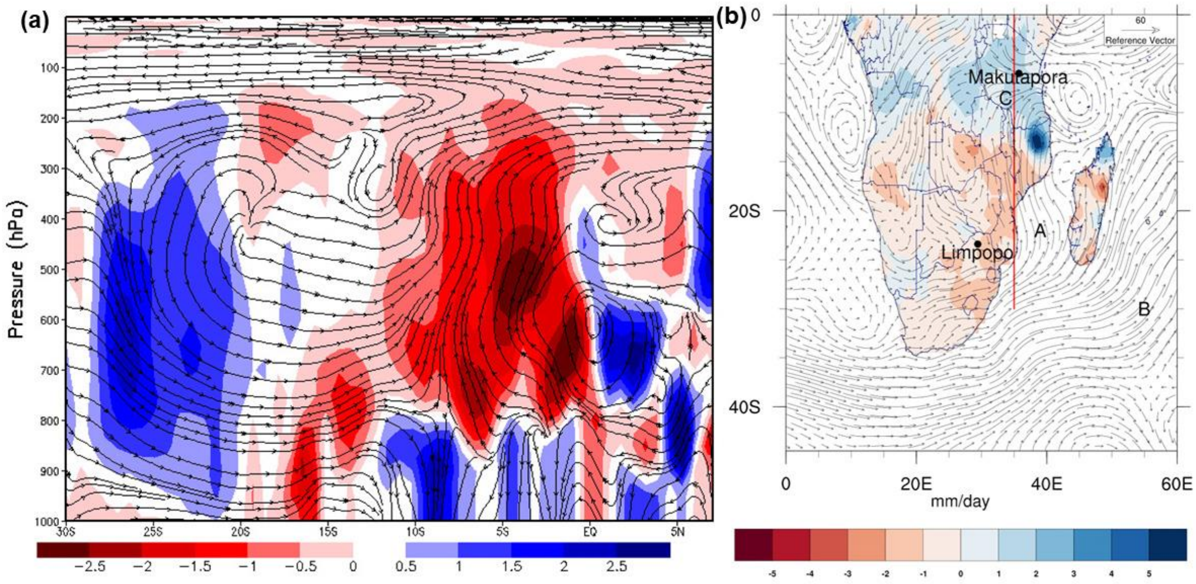

Fig. 2. Circulation anomalies for October-April 2015-2016. (a) Latitude-height transect plot of anomalous meridional overturning circulation (streamlines of vertical and meridional wind) and vertical velocity anomalies (m s^{-1}, shaded) averaged over the 35-37^{o}E. This latitude transect is shown as a red line on the map in Fig. 2(b). (b) Vertically integrated moisture flux anomalies (g kg^{-1}m s^{-2}, vectors) and rainfall anomalies (mm day^{-1}, shaded).

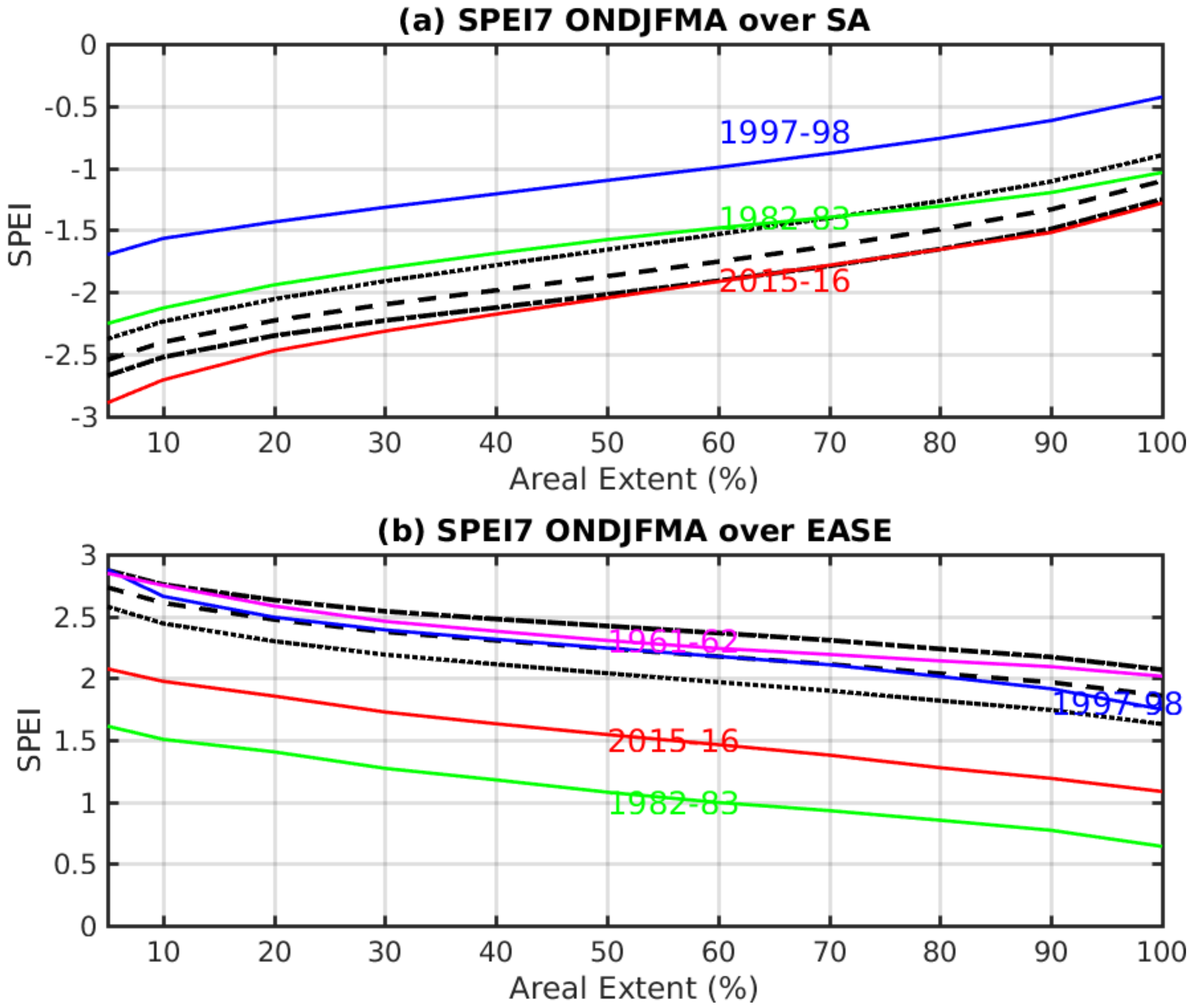

Fig. 3. Intensity-Areal extent-Frequency (IAF) curves (See Section 2.1 and Section S2 for details of method) estimated from the seasonal mean SPEI-7 (derived with Penman-Monteith PET, see text for uncertainty ranges) over (a) the southern Africa domain (10.5°-35.5°S, see box in Fig. 1a); (b) the east Africa domain 30°-40°E, 4°-12°S, see box in Fig. 1a). On the x-axis is the areal extent over which the SPEI is averaged and the y-axis is the SPEI-7 drought intensity. Solid coloured lines show the IAF curves for the study El Niño event years; 2015-16 (red), 1997-98 (blue), 1982-83 (green) and (in (b) only) the 1961-62 Indian Ocean Zonal Mode event (purple). Black lines are the IAF curves for selected benchmark return periods, from top to bottom in (a) (and bottom to top in (b)), 50 years (dotted), 100 years (dashed) and 200 years (dot-dashed).

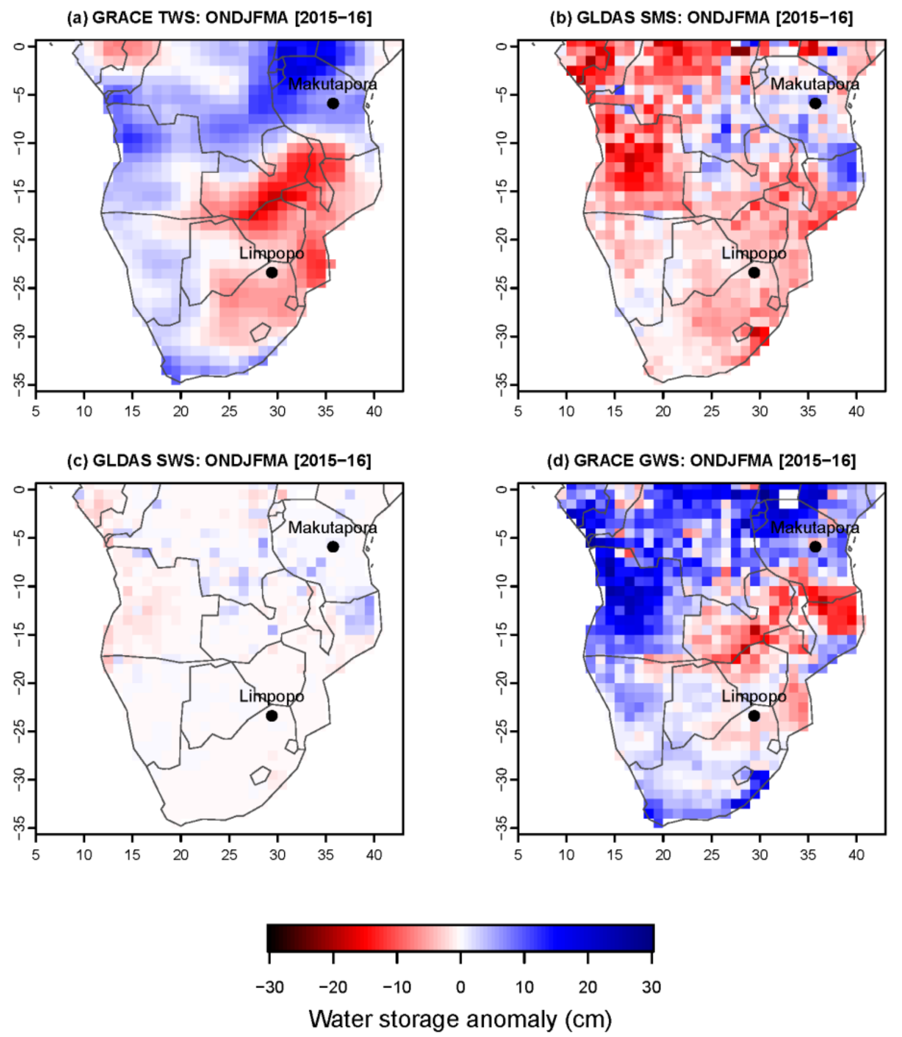

Fig. 4. Water storage anomaly components (cm) over the study domain for the wet season (October-April) of 2015-16 minus long term annual mean 2003-15. (a) GRACE ensemble mean total water storage anomaly (ΔTWS, from CSR, JPL-Mascons, GRGS GRACE products); (b) GLDAS ensemble mean soil moisture storage anomaly (ΔSMS, 4 land surface models: CLM, NOAH, VIC, MOSAIC); (c) GLDAS ensemble mean surface runoff or surface water storage anomaly (ΔSWS, from 4 land surface models: CLM, NOAH, VIC, MOSAIC); and (d) GRACE-GLDAS derived ensemble mean groundwater storage anomaly (ΔGWS, from 3 estimates of ΔGWS from 3 GRACE products).

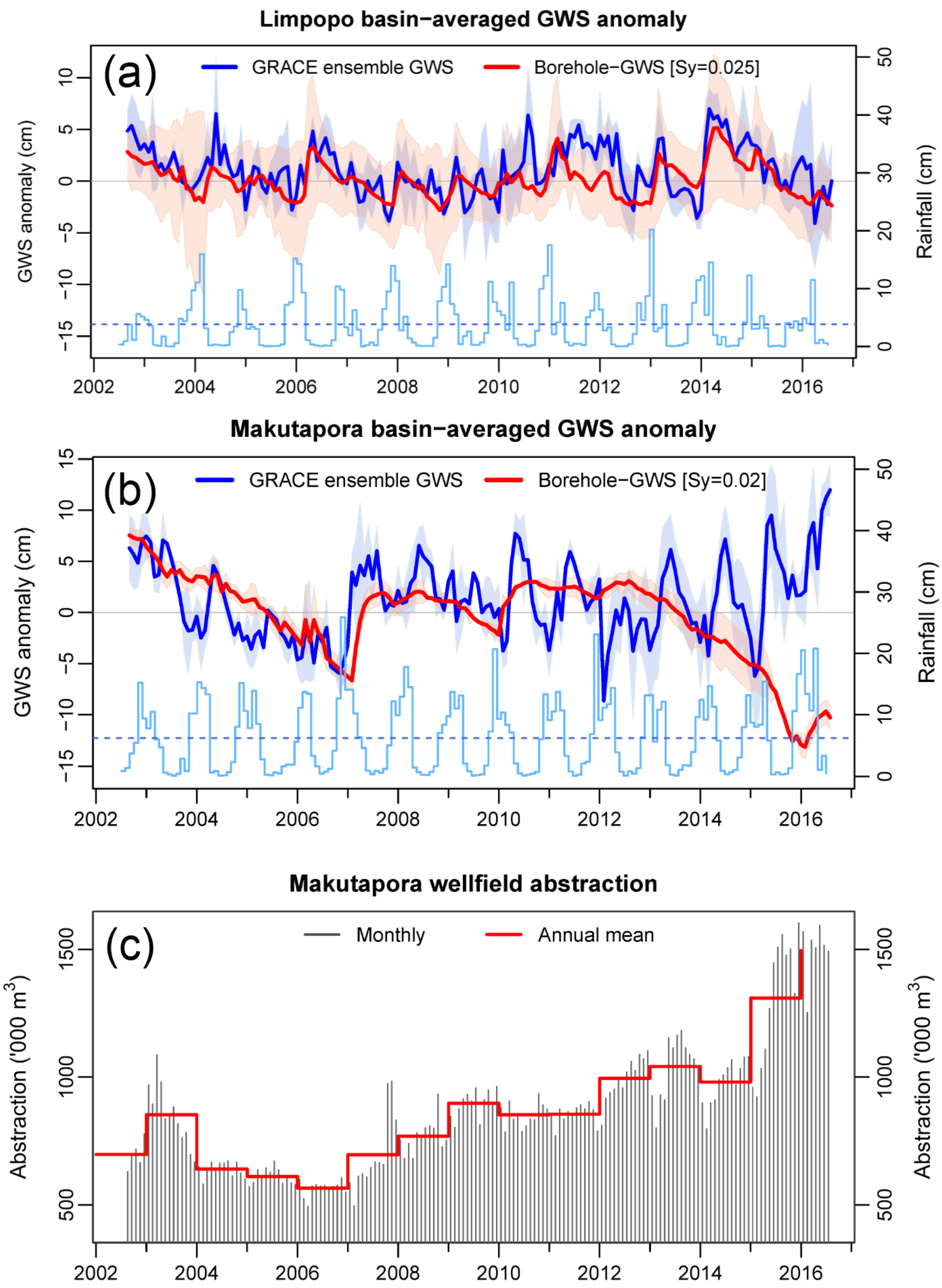

Fig. 5. (a) Time series of estimates of monthly ΔGWS anomaly (cm) at Limpopo from August 2002 to July 2016 derived from GRACE averaged over an area approximately ~120 000 km^2 (bold blue line is the mean of CSR, JPL-Mascons and GRGS products, light blue shading representing uncertainty across the three products and four LSMs) and piezometry (red line, mean of all stations, red shading represents uncertainty). Monthly rainfall (from GPCP product, cm) shown as bars with mean monthly rainfall indicated by a dashed line. (b) As (a) but for Makutapora. (c) Monthly groundwater abstraction at Makutapora.

The El Niño event of 2015-16: Climate anomalies and their impact on groundwater resources in East and Southern Africa

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Supplementary Information

S1. Climatological context: El Niño and other drivers of climate over EASE/SA, the 2015-16 El Niño event and climate anomalies over SA

The climatological mean austral summer wet season of October-April rainfall (Fig. S1(a)) shows a maximum extending Northwest-Southeast from Democratic Republic of Congo (DRC)/Angola in the west, across Zambia, Malawi to northern Mozambique in the East. The leading mode of interannual variability in rainfall and SPEI-7, is a north/south dipole pattern of opposing anomalies across EASE and SA, with a divide at ~11^{o}S, the approximate mean latitude of rainfall maximum and is strongly related to ENSO. This structure clearly evidenced by the leading Empirical Orthogonal Function (EOF) of SPEI-7 (Fig. S1(b)) which explains 21.5% of total variance. The time coefficients correlate strongly with tropical SSTs (Fig. S1(d)) highly characteristic of the ENSO SST anomalies in both the Pacific and Indian Oceans, notably the SW/NE positive/negative correlation dipole across the southwest/equatorial Indian Ocean (e.g. Lindesay, 1988; Reason *et al.,* 2000, Lazenby *et al.,* 2016). As such, for Africa South of the equator the leading mode of climate variability is strongly related to ENSO, with wet (dry) anomalies during El Niño (la Niña) events across EASE (SA). The EOF pattern is largely insensitive to the length of choice of months in the wet season. This north-south dipole response across EASE/SA to ENSO has been well documented previously (Ropelewski and Halpert, 1987; Janowiak, 1988; Goddard and Graham, 1999; Manatsa *et al.*, 2011), although the physical mechanisms of teleconnection remain elusive (see Blamey *et al.* 2018 for a summary).

The climate anomaly pattern during 2015-16 was highly characteristic of this mode (compare Figs. 1(a) and S1b). Very strong SST anomalies over the Pacific and elsewhere in the tropics during 2015-16 (Fig. S1(d)) were associated with a strong north/south dipole in rainfall with drought in SA (Fig. 1(a)). The socio-economic impacts were pronounced, with much of SA affected by drought, leading to a regional drought disaster declaration by the Southern Africa Development Community (SADC). By September 2016, six SADC countries had declared 'national drought emergencies' (Botswana, Namibia Lesotho, Malawi, Swaziland and Zimbabwe) with drought emergency declared for seven of the South Africa's nine provinces, and a temporary red alert also declared for central and Southern provinces of Mozambique (SADC 2016a). The drought resulted in an extensive loss of crops and livestock, an increase in food prices, driving an estimated 39 million people into deeper food insecurity (SADC 2016a; 2016b; Archer *et al.*, 2017). Surface water shortages further affected electricity generation and domestic supply, affecting economic activity and human health (SADC, 2016a; Siderius *et al.* 2018).

The 2015-16 El Niño was without doubt one of the strongest on record, and by some indicators was actually the strongest. There are many measures of ENSO strength (see e.g. https://www.esrl.noaa.gov/psd/enso/dashboard.html), which provide a mixed picture on the relative strength of the major events. 2015-16 appears strongest based on the Niño 3.4, Niño 4 and Bivariate El Niño – Southern Oscillation index, whilst 1997-98 is the strongest based on the (East pacific Niño 3 and 1+2 SST indices, east Pacific heat content and the Multivariate El Niño index. However, 2015-16 was certainly more persistent that 1997-98 with many indices turning positive at some time in 2014 related to the El Nino event that was predicted in 2014 but did not develop fully until 2015-16 (Levine and McPhaden, 2016).

However, there is substantial diversity in the character of El Niño events, in terms of both (i) the structure and magnitude of anomalies in the Pacific sector. For example, 2015-16 and 1997-98 differed in that the former was stronger in the Central Pacific sector (Niño3.4 and Niño SST region) and the latter in the East Pacific (Niño 1+2 and Niño 3 SST regions) (ii) the state and evolution of other regional drivers of climate variability which interact with ENSO teleconnection processes, such that the remote impacts over Africa can be quite variable (e.g. Ratnam *et al.*, 2014; Preethi *et al.*, 2015, Hoell *et al.*, 2017; Blamey *et al.*, 2018). Across Southern Africa (SA) multiple regional structures of ocean and atmospheric variability modulate the impacts of ENSO including the South Indian Ocean dipole (Reason, 2001) as well as the Angola low and Botswana High atmospheric features (Blamey *et al.*, 2018). Furthermore, intraseasonal variability associated with the Madden Julian Oscillation, with 30-60 day timescales can also modulate interannual drivers of variability, particularly over East Africa (Berhane and Zaitchik, 2014).

Over East Africa rainfall is more strongly related to the state of the Indian Ocean than to ENSO. The Indian Ocean Zonal mode (IOZM), an east-west pattern of atmosphere-ocean variability across the Equatorial Indian ocean, strongly modulates the regional Walker circulation and hence rainfall over East Africa. During positive IOZM events warmer ocean temperatures in the equatorial west Indian Ocean and cooler temperatures in the east lead to enhanced rainfall over EASE, with negative IOZM leading to a reduction in rainfall (see Nicholson 2017 for a review and references therein). The impact of ENSO on EASE is therefore intimately connected to the state of the IOZM (Black *et al.*, 2003, Manatsa *et al.*, 2011). During 2015-16 the IOZM was only weakly positive (see SST anomalies in Fig. S1(d)) and the seasonal de-trended IOZM index (Saji *et al.*, 1999) in 2015-16 was ranked 16th out of 150 years. As a result, the mean equatorial zonal Indian Ocean Walker cell with ascent (descent) in the east at ~100^{o}E (west at ~50^{o}E) of the basin is only weakly perturbed. The zonal cross section over the East Africa-Indian Ocean sector indicates that enhanced large-scale uplift is limited to a quite restricted region of EASE from ~33^{o}-40^{o}E. In this way, the weak reorganisation of the Indian ocean Walker circulation led to rather moderate rainfall anomalies over EASE (Section 3.1).

S2. SPEI-7 Intensity-Area-Frequency (IAF) curves and associated return period estimates, and attribution of anthropogenic influence on the SA drought 2015-16

Droughts are spatially extensive but variable features. We represent the spatial extent using IAF curves which show the intensity of SPEI-7 water balance anomalies across all spatial scales within a study domain. IAF curves are independent of the precise spatial patterns of SPEI-7 anomalies, and as such allow us to compare droughts between individual years, and to calculate the return periods for drought events across scales. This direct comparability of SPEI-7 IAF curves is valuable since no two drought events have exactly the same spatial pattern. The IAF curves are derived using the method of Mishra and Cherkauer (2010) separately over the two study domains of EASE and SA, by calculating the mean SPEI-7 value of grid cells lying within various areal extent intervals: The areas covered by the lowest (for SA) or highest (for EASE) 5th, 10th, 20th…100th areal percentiles of SPEI grid cell values within the domain area i.e. when all grid cells are ranked. This allows, for each season, the mean SPEI-7 IAF curve to be plotted (see Fig. 3).

We then estimate the return period of the 2015-16 El Niño event by comparing the observed SPEI-7 IAF curve of 2015-16 with IAF curves representing various 'benchmark' return periods (Fig. 3) and finding the closest match, by least squared error. Estimating these benchmark return periods of drought events is challenging given the relatively short observational record for what are relatively long duration events, and indeed because of non-stationarity in climate records under a changing climate. We address both these challenges in our approach. To counter the problem of insufficient sampling of the extreme tail of the distribution, we increase our sample of climate events beyond the observed record using large ensembles of climate model simulations from the HAPPI experiment (Mitchell *et al.*, 2017). HAPPI is designed specifically to quantify climate extremes, through the use of relatively high model resolution and large initial-condition ensembles. We use precipitation data from four atmospheric models, namely HadGEM3, CAM5, MIROC5 and NorESM, (degraded to common resolution of 1^{o}) each with 10 ensemble members, run over the period ~1950s-2010s, forced with observed SSTs and ‘historical’ greenhouse gases and aerosol radiative forcings. These simulations provide about 2400 years of simulated data, with greater statistical definition of the extreme tail of the distribution required for the extreme events, notably the 2015-16 drought over SA which is the strongest on record. As with the observations we derive the mean SPEI-7 for each areal extent interval (5th, 10th, etc. spatial percentiles over the domain), for each of the ~2400 model years. Estimation of return periods is based on the Extreme Value Theory (EVT), widely used for the description of rare climate events in the extreme tail of the parameter distribution. The Generalized Extreme Value distribution (GEV) is fitted to the distribution of only the extreme SPEI-7 values, for each areal extent separately (using maximum likelihood estimation and a chi-squared goodness-of-fit test, Coles *et al*., 2001). This distribution of extremes (‘block maxima’) is composed of the most intense SPEI-7 values (for drought over the SA domain SPEI-7 is multiplied by -1) within non-overlapping ‘blocks’ of 30 years, a standard climatological period. Then, return periods are estimated by inverting the resulting GEV cumulative probability distribution for a range of periods from 30-300 years, for each areal extent separately, providing IAF curves for benchmark return periods (see Fig. 3). Whilst our approach is similar to previous drought analyses (e.g. Robeson, 2015) we recognise a number of caveats. First, the estimated return periods are sensitive to the arbitrary choice of block size and we estimate the uncertainty associated with this using periods of 25-60 years. Second, whilst the large ensembles provided by the HAPPI experiment are designed specifically for analysis of extremes they necessarily provide only a partial representation of the climate variability ‘space’.

For estimation of return periods shorten than the duration of one ‘block’ (30 years), we follow Mishra and Cherkauer (2010) and Philip *et al.* (2018) in fitting a distribution to the historical record of SPEI-7 data. For each areal extent interval (5^{th}, 10^{th}, etc. spatial percentiles) we fit a GEV distribution to the 116 historical SPEI-7 data points. We then invert the cumulative distribution to derive return periods for every spatial percentile, giving a set of IAF benchmark return period curves. Finally, we conduct all the above IAF curve return period analysis using SPEI-7 derived with each of the three PET equations and provide the average return period estimates and the associated range to represent this component of uncertainty.

It is likely that anthropogenic climate change is, and will continue to, affect large-scale hydrology. As such, climate risks are changing and non-stationarity in climate records complicates the interpretation of return periods. However, the IPCC recent assessment report concludes that there is only low confidence in detection and attribution of observed changes in drought extremes globally (Bindoff *et al.*, 2013), largely due to uncertainties in distinguishing relatively small trends in precipitation from decadal variability, especially given limitations in precipitation data. Nevertheless, attribution of recent temperature rises is robust even down to the regional/continental scale (Bindoff *et al.*, 2013). In recent probabilistic event attribution analyses of tropical drought events the contribution of anthropogenic temperature effects is discernible, in contrast to that of precipitation (Marthews *et al.*, 2015). As such, the full causal chain from climate anomaly through water balance to agricultural drought is complex and typically not well represented in models such that attribution of drought remains extremely challenging. Therefore, here we estimate the effects purely of anthropogenic temperature trends on drought risk over SA through a simplified attribution experiment. The SPEI-7 IAF return period analysis above is repeated, but in deriving the benchmark return period curves the temperature data, used in calculating PET, has the signal of anthropogenic climate change removed. Specifically, PET is estimated using the HAPPI multi-ensemble mean temperature from a counterfactual world without human influence on radiative forcing: the 'natural' runs, in which only the natural forcings (solar variability and volcanic aerosols) are provided to the models. To ensure space-time consistency in all the climate variables whilst changing the temperature data, we used the 30-year smoothed temperature from the 'natural' model runs to which is added the anomalies of temperature from the 'historical' run with respect to a 30-year running mean. Not that we derive the SPEI-7 over both datasets merged together so that the effect of the temperature perturbation between the 'natural' and 'historical' runs is reflected in the resulting SPEI-7 values, given that the index is standardised across the timeseries. The benchmark return period IAF curves are then derived from the SPEI-7 values for each dataset separately. Thus, comparing the estimated SPEI-7 IAF return periods from the climate with 'historical' temperature with those from a counterfactual climate with the 'natural' only temperature, provides an indication of the influence of the anthropogenic temperature trend effects on drought risk over SA. We note that the SPEI is quite temperature dependent through PET calculation such that other drought indices may yield different sensitivity to warming.

We must emphasise that this analysis deliberately considers only the effects of the slowly evolving anthropogenic influence on temperature. We do not consider anthropogenic influences on rainfall and the other determinants of PET i.e. wind speed, humidity, radiation budget, no any changes to variability in temperature or any other variables. Further, the difference in model estimated temperatures between the 'natural' and 'historical' run will include the effects not just of anthropogenic radiative forcing but also the surface energy budget which itself is affected by precipitation and other near surface variables whose response to radiative forcing we do not consider. However, in utilising a large model ensemble to define the statistics of extreme events, we retain some features of the probabilistic event attribution method (e.g. Allen *et al.*, 2003, Stott *et al.*, 2014) but focus solely on that aspect of climate change (near surface temperatures) for which we have greatest confidence in the ability of models to represent with credibility.

S3. Groundwater storage estimates from GRACE and LSMs

To address uncertainty associated with different GRACE processing strategies to resolve ΔTWS (Eq. 1) we apply an ensemble mean of three GRACE TWS. Namely, the CSR land (version RL05.DSTvSCS1409, Swenson and Wahr, 2006; Landerer and Swenson ,2012) and JPL Global Mascon (version RL05M_1.MSCNv01, Watkins *et al.*, 2015; Wiese *et al.*, 2015) solutions, from NASA's *GRCTellus* data dissemination site (http://grace.jpl.nasa.gov/data), and a third GRGS GRACE solution (CNES/GRGS release RL03-v1) (Biancale *et al.*, 2006) from the French Government space agency, Centre National D'études Spatiales (CNES).

GRCTellus CSR land solution (version RL05.DSTvSCS1409) is post-processed from spherical harmonics released by the Centre for Space Research (CSR) at the University of Texas at Austin. *GRCTellus* gridded datasets are available at a monthly time step and a spatial resolution of 1° × 1° (~111 km at equator) though the actual spatial resolution of GRACE footprint is ~450 km or ~200,000 km^2 (Scanlon *et al.*, 2012). To amplify TWS signals we apply the dimensionless scaling factors provided as 1° × 1° bins that are derived from minimising differences between TWS estimated from GRACE and the hydrological fields from the Community Land Model (CLM4.0) (Landerer and Swenson, 2012). JPL-Mascons (version RL05M_1.MSCNv01) data processing involves the same glacial isostatic adjustment correction but applies no spatial filtering as JPL-RL05M directly relates inter-satellite range-rate data to mass concentration blocks (mascons) to estimate monthly gravity fields in terms of equal area 3° × 3° mass concentration functions in order to minimise measurement errors. Gridded mascon fields are provided at a spatial sampling of 0.5° in both latitude and longitude (~56 km at the equator). Similar to *GRCTellus* CSR product, dimensionless scaling factors are provided as 0.5° × 0.5° bins (Shamsudduha *et al.*, 2017) that also derive from the Community Land Model (CLM4.0) (Wiese *et al.*, 2016). The scaling factors are multiplicative coefficients that minimize the difference between the smoothed and unfiltered monthly ΔTWS variations from the CLM4.0 hydrology model (Wiese *et al.*, 2016). GRGS monthly GRACE products (version RL03-v1) are processed and made publicly available (http://grgs.obs-mip.fr/grace) by CNES (Shamsudduha *et al.*, 2017). Further details on the Earth's mean gravity-field models can be found on the CNES official website of GRGS/LAGEOS (http://grgs.obs-mip.fr/grace/). GRACE ΔTWS time-series data have some missing records as the satellites are switched off for conserving battery life (Shamsudduha *et al.*, 2017); these missing records are linearly interpolated (Shamsudduha *et al.*, 2012).

To derive ΔGWS from GRACE ΔTWS (eq. 1) we use simulated soil moisture to represent ΔSMS and surface runoff, as a proxy for ΔSWS (Mishra *et al.*, 2016), from LSMs within NASA's Global Land Data Assimilation System (GLDAS). We apply monthly ΔSMS and surface runoff data at a spatial resolution of 1° × 1° from 4 GLDAS LSMs: The Community Land Model (CLM, version 2) (Dai *et al.*, 2003), NOAH (version 2.7.1) (Ek *et al.*, 2003), the Variable Infiltration Capacity (VIC) model (version 1.0) (Liang *et al.*, 2003), and MOSAIC Mosaic (version 1.0) (Koster and Suarez, 1992). The respective total depths of modelled soil profiles are 3.4 m, 2.0 m, and 1.9 m and 3.5 m in CLM (10 vertical layers), NOAH (4 vertical layers), and VIC (3 vertical layers), and Mosaic (3 vertical layers) (Rodell *et al.*, 2004). In the absence of in situ ΔSMS and ΔSWS data in the study areas, we apply an ensemble mean of the 4 LSMs-derived ΔSMS and ΔSWS data in order to disaggregate GRACE ΔTWS signals across our study regions, for the period August 2002 to July 2016, similar to the approach applied for other locations by Shamsudduha *et al.* (2012, 2017). To help interpretation of these mean

ΔGWS signals we also present the total uncertainty in estimates of ΔGWS which result from the uncertainty in estimates of ΔTWS, ΔSMS and ΔSWS (blue shading in Fig. 5(c)). The uncertainty in these individual water balance components is shown in Fig. S2 i.e. the range in estimated GRACE ΔTWS across the three retrieval estimates, and the ranges in estimates ΔSMS and ΔSWS across the four LSMs. Overall, the total uncertainty in ΔGWS can be substantial and receives roughly equal contribution from uncertainty in ΔTWS and ΔSMS with uncertainty in ΔSWS important only occasionally. There is some indication that during the periods of greatest ΔGWS uncertainty, the ΔTWS uncertainty is most important e.g. 2009-10 and 2015-16 at Limpopo. To understand this uncertainty in GRACE ΔTWS further we show the time series of the three individual ΔTWS retrievals of CSR, JPL-Mascons and GRGS (Fig. S3), which we examine in more detail in Section 3.2.2. For further understanding of the uncertainty in the estimates water storage from LSMs with respect to GRACE readers are referred to Scanlon *et al.* (2018).

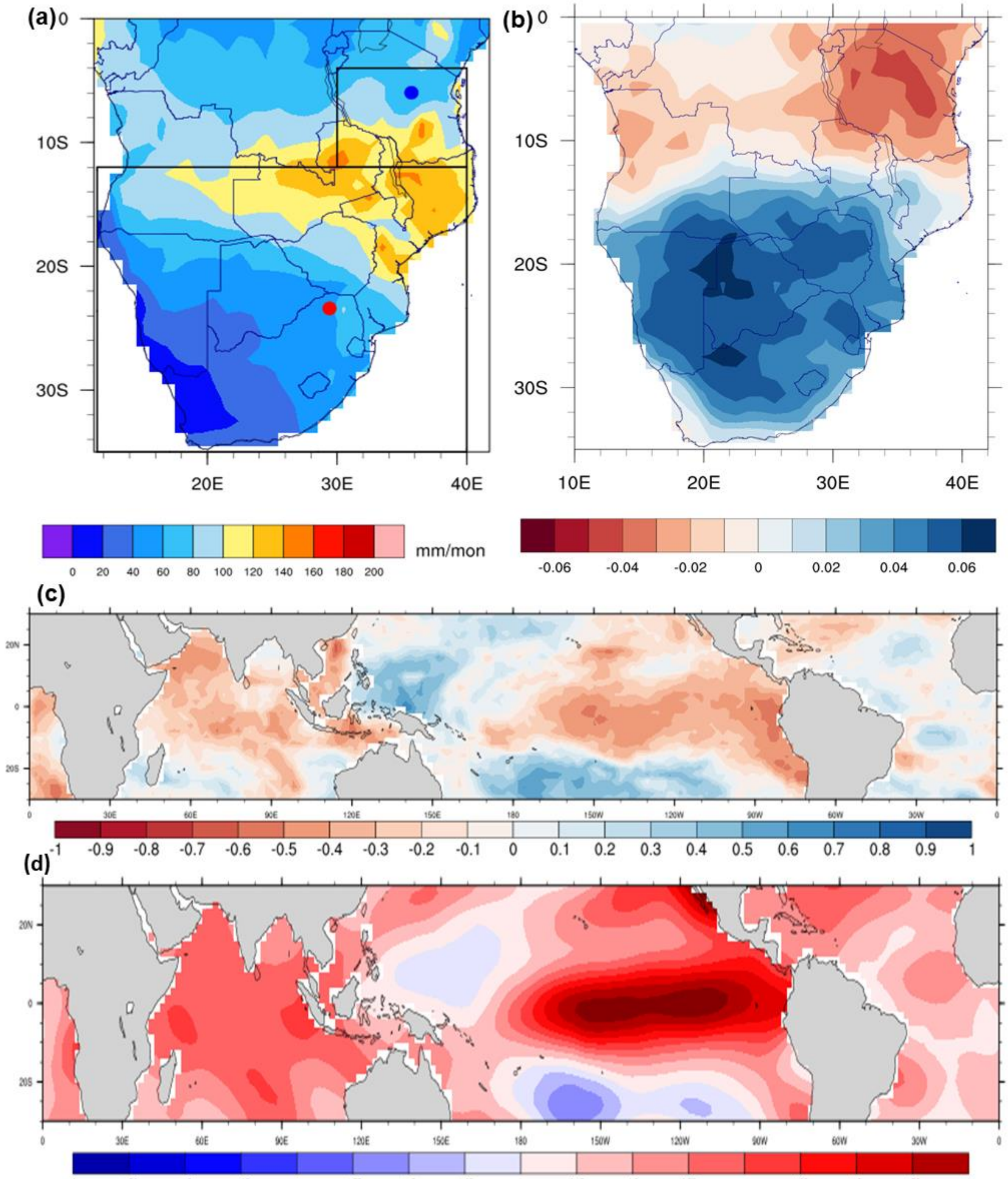
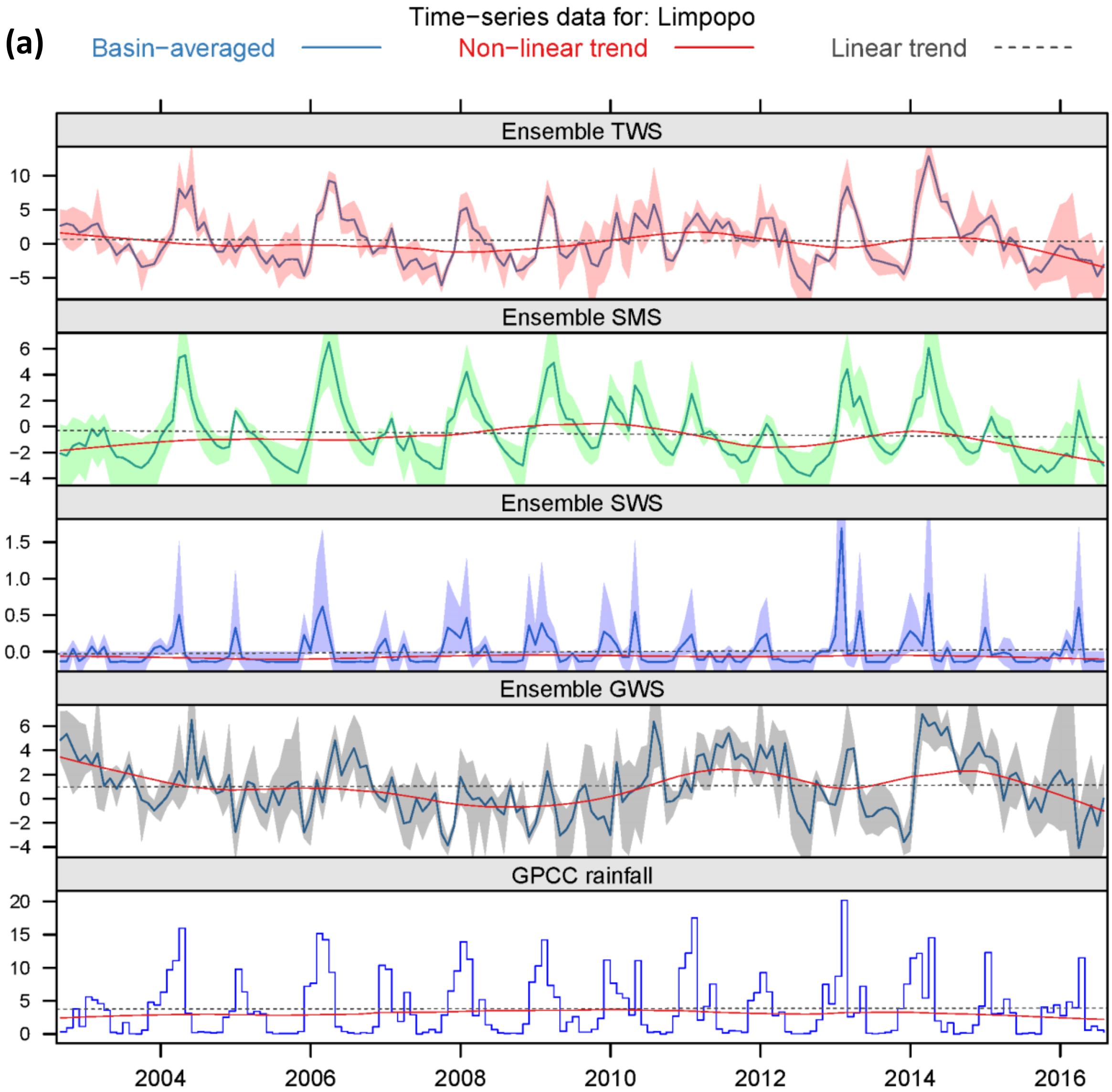


Fig. S1. (a) Climatological precipitation for the October-April season for the period of 1901-2016 (mm month^{-1}). Boxes in Fig. S1(a) show the EASE (small box) and SA (big box) domains used in the IAF analysis (see Section 2.1). The blue and red filled circles denote the piezometer observation locations at Makutapora, Tanzania and Limpopo, South Africa, respectively. (b) Leading mode of interannual October-April variability calculated using the empirical orthogonal function (EOF) analysis of de-trended rainfall of GPCC. (c) Correlation between coefficients of EOF1 (Fig. S1(b)) and global SST (October-April mean) 1901-2016. (d) SST anomalies (K) October-April 2015-16, with respect to 1980-2010 reference period



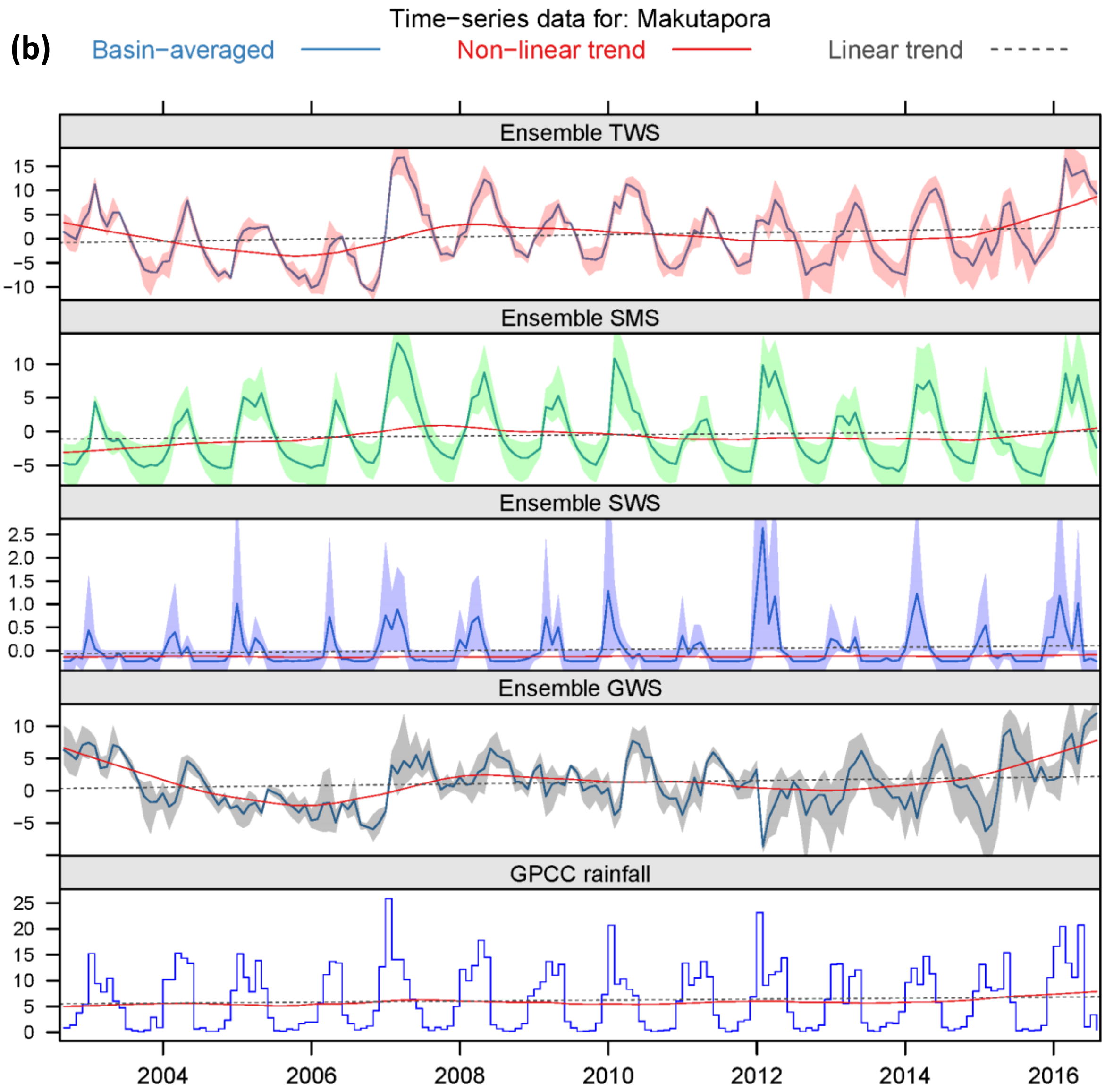


Fig. S2: Time series of monthly estimates of anomalies in the individual components of water balance (lines) and the associated uncertainty range (shaded). From top to bottom TWS from GRACE; SMS and SWS both from LSMs; the residual GWS; observed GPCC rainfall, (all in cm) at (a) Limpopo, and (b) Makutapora.

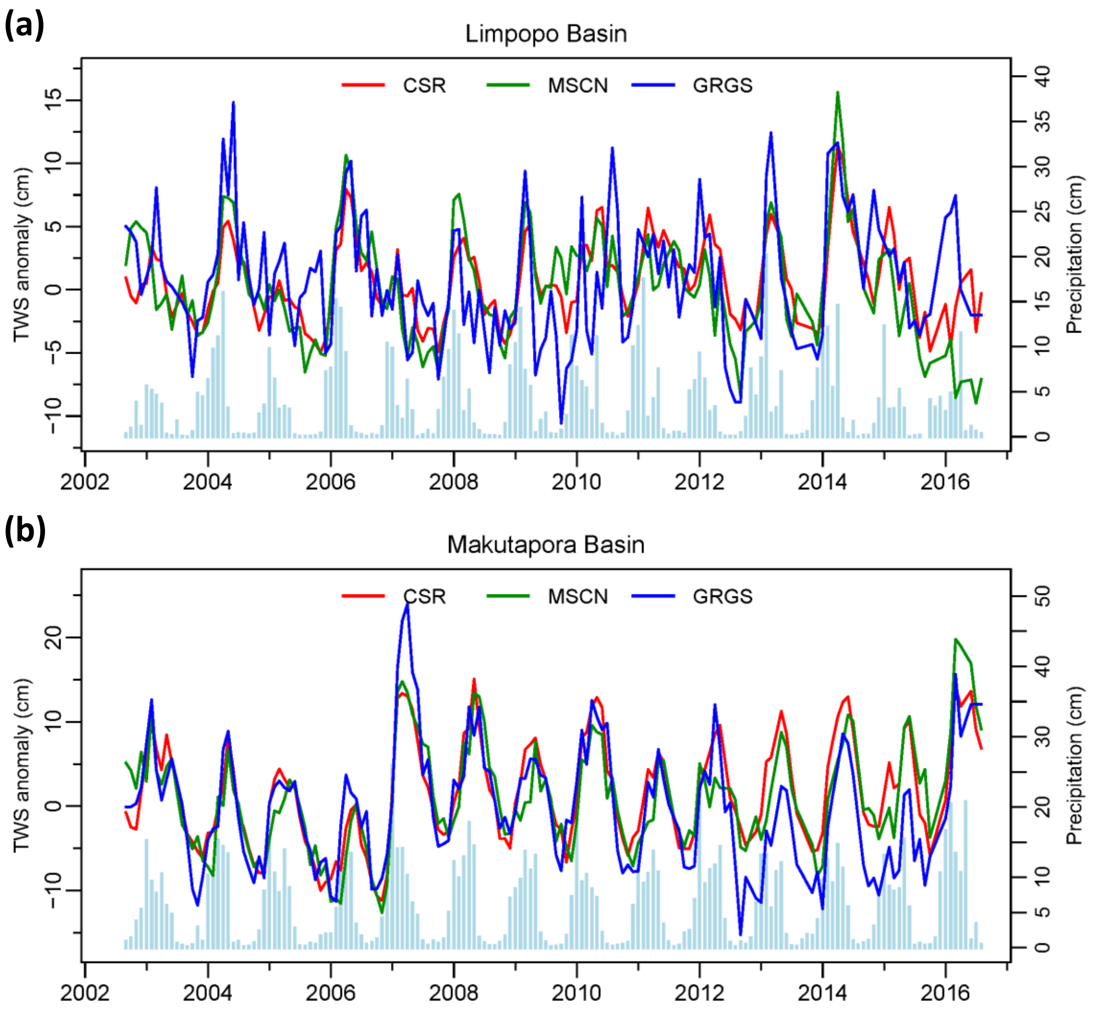


Fig. S3: (a) Time series of estimates of monthly ΔTWS anomaly (cm) at Limpopo from August 2002 to July 2016 (averaged over an area approximately ~120 000 km^2) derived from the three individual GRACE retrievals of CSR (red), JPL-Mascons (green) and GRGS (blue). Monthly rainfall (from GPCP product, cm) shown as bars. (b) As (a) but for Makutapora.

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