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2	Africa: implications for groundwater resources management
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Key words: GRACE, climate change, groundwater management, groundwater storage, SubSaharan Africa

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22 Abstract

23 The links between climate variability, depicted by times series of oceanic indices, and changes in 24 total water and groundwater storage are investigated across nine large aquifer basins of the 25 African continent. The Gravity Recovery and Climate Experiment (GRACE) mission's 26 observations represent a remarkable tool that can provide insight into the dynamics of terrestrial 27 hydrology in areas where direct in-situ observations are limited. In order to evaluate the impact 28 of inter-annual and multi-decadal climate variability on groundwater resources, this study 29 assesses the relationship between synoptic controls on climate and total water storage estimates 30 from (i) GRACE from 2002 to 2013 and (ii) a two-variables climate-driven model that is able to 31 reconstruct past storage changes from 1982 to 2011. The estimates are then compared to time 32 series of groundwater levels to show the extent to which total water storage covaries with 33 groundwater storage. Results indicate that rainfall patterns associated with the El Niño Southern 34 Oscillation (ENSO) are the main driver of inter-annual groundwater storage changes, whereas 35 the Atlantic Multi-Decadal Oscillation (AMO) plays a significant role in decadal to multi-36 decadal variability. The combined effect of ENSO and AMO could trigger significant changes in 37 recharge to the aquifers and groundwater storage, in particular in the Sahel. These findings could

- help decision-makers prepare more effective climate-change adaptation plans at both nationaland transboundary levels.
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41 NOTE TO COPYEDITOR - PLEASE INSERT THE FOLLOWING AS A FIRST-PAGE 42 FOOTNOTE: 43 This article is part of the topical collection "Determining groundwater sustainability from long44 term piezometry in Sub-Saharan Africa" 45

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48 **1. Introduction**

49 Africa faces major water resources management challenges, largely because water is unevenly 50 distributed over the continent and over time. About 64% of the population rely on limited and 51 highly variable amounts of water, and 25% of the population experience difficulties in water use 52 due to accessibility or mobilizations issues (e.g. water infrastructure, flow controls, costs) 53 (Vorosmarty et al., 2005). As a result of rapid population growth and higher industrial activity, water demand in Africa is projected to more than double by the end of the 21st century (Wada 54 55 and Bierkens, 2014), which may compromise the future livelihoods of millions of people and 56 their living standards. Global climate change and variability is expected to exacerbate this issue 57 as it will bring more extreme climate conditions such as droughts (Prudhomme et al., 2014; 58 Trenberth et al., 2014; Malherbe et al., 2016). Groundwater plays an important role in society's 59 adaptation to climate change and variability, especially because it is more resilient to the effects 60 of climate change than surface water (Green et al., 2011; Treidel et al., 2012; Van der Gun, 2012; 61 Taylor et al., 2013a). Groundwater's unique buffer capacity provides a major strength to reduce 62 the risk of temporary water shortage, and to create conditions for survival in areas were climate 63 change is expected to cause water stress (Falkenmark, 2013).

64 An estimated 75% or more of Africans use groundwater as their main source of drinking water 65 (UNEP, 2010), particularly in rural areas that rely on low-cost dug wells and boreholes. There is 66 very limited reliable and comprehensive statistics on groundwater use in Africa, but previous 67 assessments indicate an underutilized potential to support irrigated agriculture as most farming in Africa is currently rainfed (Wani et al., 2009). Groundwater is over-exploited for irrigation in 68 69 many parts of the world (Famiglietti, 2014; Konikow 2015) including Asia where 14% of 70 cultivated land is irrigated with groundwater (Siebert et al., 2010) but in Africa ~1% of the cultivated land (about 2×10^6 hectares) is irrigated with groundwater (Altchenko and Villholth, 71 72 2015). In contrast to other regions in the world such as Western Mexico, the High Plains in the 73 central U.S., the Middle East, North-East Pakistan, North-West India, and North-East China, 74 most of Sub-Saharan Africa has not yet experienced the "groundwater crisis" (Famiglietti, 2014) 75 caused by the widespread over-abstraction of groundwater to support large-scale agriculture. 76 Moreover, some major African aquifers tend to coincide with areas of relatively lower 77 population density and water demand (e.g. the Sahel aquifer Basins, the Congo Basin in Central 78 Africa, and the Kalahari Basins in Southern Africa) (Foster et al., 2006; Wada et al., 2010; 79 Gleeson et al., 2012; MacDonald et al., 2012). Many African countries and/or joint bodies in 80 charge of implementing transboundary water agreements thus have an opportunity to anticipate 81 future groundwater use and management challenges through planning, sustainable utilization, 82 and effective protection of groundwater resources (Tuinhof et al., 2011; Gorelick and Zheng, 83 2015).

However, the development of long-term effective and reliable groundwater management strategies for coping with water scarcity threats and climate variability and change in Africa is undermined by the lack of adequate data for decision-making (Bates et al., 2008). In recent

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87 years, there has been a substantial decline in hydrometeorological data collection and 88 management in Africa (Houghton-Carr and Fry, 2006; Robins et al., 2006). Decades ago, Africa 89 had a relatively dense network of stations to measure rainfall, temperature and other weather 90 data, but some weather centres have aged badly because of reductions in budgets for field 91 maintenance and inspection, and many of these stations are no longer operating (Giles, 2005). 92 The current density of hydrometeorological stations in Africa is eight times lower than the 93 minimum recommended by the World Meteorological Organization (WMO, 1996). Many governments have a limited ability to collect the data needed for long-term water resources 94 95 management, and current efforts have mainly focused on rainfall and river flow data collection. 96 As a result, most African countries lack groundwater-monitoring stations and this limits the 97 understanding of the response of groundwater to human and natural conditions (Gaye and 98 Tindimugaya, 2012).

99 Over the last decade, significant advances in the remote sensing techniques have led to a more 100 complete overview of the water cycle at the global scale. Launched in March 2002, the Gravity 101 Recovery and Climate Experiment (GRACE) is the first satellite mission able to provide global 102 observations of terrestrial water storage changes (Δ TWS) (Richey et al., 2015; Chen et al., 2016). 103 Given that the dynamics of groundwater are affected by inter-annual to multi-decadal climate 104 variability (Gurdak et al., 2007; Kuss and Gurdak, 2014), longer observations than GRACE's current 15 year record (2002 to 2017) are desirable to better evaluate the past and current 105 106 evolution of groundwater resources, as well as to provide pointers for the future.

107 To overcome GRACE's time frame limitation and the lack of adequate long-term piezometry 108 data, this study used an approach to reconstruct past water storage variations in major aquifers 109 across Africa through a climate-driven model using precipitation and actual evapotranspiration

110 data from global datasets over the period of 1982 to 2011. Validation of the results is carried out 111 by comparing the results of modeled total water storage changes (ΔTWS_{MODEL}) with GRACE-112 based total water storage changes (ΔTWS_{GRACE}) estimates from 2002 to 2013. The model and 113 GRACE-based estimates are then compared to long-term piezometry measurements to show the 114 extent to which total water storage changes covary with observed groundwater storage changes 115 $(\Delta GWS_{OBSERVED})$. Using this approach also allows one to quantify teleconnections between total 116 water and groundwater storage changes with global-scale climatic oscillations such as the El 117 Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Atlantic Multidecadal 118 Oscillation (AMO).

119 Acronyms and abbreviations are given in the Appendix.

120

121 2. Background

122 2.1. Study areas

Nine large aquifer systems in Africa were selected for this study on the basis of hydrogeological,climate and governance conditions as presented in Table 1 and Figure 1.

The distribution of aquifers in Africa is now reasonably mapped following long-term programmes launched in the 1960s by national and international agencies and supported variously by UNESCO, IAEA, and British, French, German and Dutch technical assistance. These efforts were subsequently integrated by the International Association of Hydrogeologists (IAH)/UNESCO/BGR WHYMAP Africa Groundwater Resources Map in 2008, which was the baseline for the first quantitative maps of groundwater resources in Africa (MacDonald et al., 2012). Approximately 45% of the African land surface is underlain by large sedimentary basins hosting relatively homogeneous aquifers that may offer good conditions for groundwater
abstraction. Approximately 11% of the land has a geologically complex structure, highly
productive aquifers in heterogeneous folded or faulted regions in close vicinity to non-aquifers.
Almost half of the territory (44%) consists of regions with only limited groundwater resources,
generally in local and shallow aquifers in weathered crystalline bedrock or alluvial deposits that
locally may be productive (BGR and UNESCO, 2008; Maurice et al., 2018).

138 With regards to storage, a considerable proportion of Africa's groundwater resources is located 139 in the large sedimentary basins in (semi)arid zones (e.g. North Africa, Sahel, and the Kalahari 140 and Karoo basins in Southern Africa) and tropical zones (e.g. the Congo Basin in Central Africa) 141 (MacDonald et al., 2012). These basins usually contain multi-layered aquifer systems with major 142 alluvial formations forming shallow unconsolidated aquifers underlain by consolidated 143 sedimentary rocks forming deeper aquifers. Even in semi-arid parts of Africa the shallow 144 unconsolidated aquifers can be recharged in response to episodic storm events, climate 145 oscillations, and land-use change (Taylor et al. 2009, 2013b). In the Sahara/Sahel aquifers, 146 isotope and hydrochemical investigations have revealed that recharge mainly occurs by direct 147 infiltration of rainwater or by river/surface water interaction as in the case of the Senegal and 148 Niger Rivers (Diaw et al., 2012; Nazoumou et al., 2015; Abdou Babaye et al., 2018). Stable and 149 radioactive isotopes contents in shallow aquifers confirm the presence of modern infiltration 150 water (Lapworth et al., 2013; Zouari, 2015). Recharge rate over these areas are usually low and 151 range from 0.1 to 5% of annual precipitation (Scanlon et al., 2006). The recharge mechanisms 152 and dynamics of the deeper aquifers is still uncertain. Data from the Sahara/Sahel tend to exhibit 153 piston-flow behavior (i.e. new water "pushing" old water downwards). Depleted stable isotopes 154 contents observed in some aquifers (Taoudeni and Iullemmeden basins) suggests the presence of palaeoclimatic water or old-recent mixed groundwater (Fontes et al., 1991; Zouari, 2015).
However, the deeper aquifers can be considered as not being actively recharged as most of the
recharge dates back to more than 5000 years ago (Edmunds, 2008).

158 Most of these aquifers located in large sedimentary basins are transboundary. More than 75 159 transboundary aquifers have been identified in Africa, but as more information and knowledge 160 becomes available this number is likely to increase (IGRAC-UNESCO, 2015). The identified 161 transboundary aquifers represent approximately 42% of African continental land area and 30% 162 of the population. Arrangements for the management of these transboundary aquifers remain 163 insufficiently developed as groundwater has been traditionally considered a national matter. Only 164 three transboundary aquifers are under an operational agreement, namely the Nubian Sandstone 165 Aquifer System (NSAS), the North-Western Sahara Aquifer System (NWSAS), and the 166 Stampriet Transboundary Aquifer System (STAS). A Memorandum of Understanding was 167 signed in 2014 for the establishment of a consultation mechanism for the Iullemmeden, 168 Taoudeni/Tanezrouft Aquifer System (ITTAS) but has not entered into force yet. Africa is 169 however the continent with the highest proportion of transboundary surface water catchments 170 under an operational arrangement (Meyer, 2016; UNESCO and UNECE, 2017). Given that 171 aquifers and river/lake basins do not necessarily coincide, the most appropriate body to oversee 172 the management of a transboundary aquifer may not necessarily be a river or lake basin 173 organization (if existent). However, these arrangements and institutions could play a crucial role 174 in promoting cooperation over transboundary aquifers through action programmes.

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INSERT TABLE 1 HERE

176

INSERT FIGURE 1 HERE

8

177 2.2. Climate variability modes in Africa

178 Exchanges between the Earth's atmosphere, oceans, cryosphere and continental hydrology give 179 rise to some natural climate fluctuations, of various periodicities. Some of the most important 180 global-scale climate oscillations on interannual to multidecadal timescales that influence local 181 water resources include the El Niño Southern Oscillation (ENSO), North Atlantic Oscillation 182 (NAO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO). These 183 natural climate oscillations are monitored using scalar-valued indices, which characterize 184 positive, negative, and neutral phases of a climate variability mode and to identify the strength of 185 these phases.

186 ENSO is considered as the most important pattern of natural interannual climate variability on 187 Earth (Palmer and Anderson, 1994). It is a coupled ocean-atmospheric phenomenon that has 188 interannual variability with irregular 2- to 7-year cycles between the warm (El Niño) and cold 189 (La Niña) phases that has been occurring for at least the past 700 years (Li et al., 2013). El Niño 190 is characterized by stronger than average sea surface temperatures in the central and eastern 191 equatorial Pacific Ocean, reduced strength of the easterly trade winds in the Tropical Pacific, and 192 an eastward shift in the region of intense tropical rainfall. La Niña is characterized by the 193 opposite – cooler than average sea surface temperatures, stronger than normal easterly trade 194 winds, and a westward shift in the region of intense tropical rainfall. Three very strong El Niño 195 events have occurred since the early 1980s, i.e. 1982–1983, 1997–1998, and more recently 2015-196 2016. Although ENSO is centered in the tropics, the changes associated with El Niño and La 197 Niña events affect climate around the world. ENSO's influence upon annual rainfall levels have 198 been reported all across Africa, particularly in Southern Africa (Manatsa et al., 2011). Droughts

199 occur most of the time during the warm phase of ENSO (Masih et al., 2014). On the other hand, 200 the trend to more La Niña-like conditions since 2000 is a likely contributing factor driving the 201 increase in Southern Africa rainfall (Maidment et al, 2015). As compared to the other African 202 regions, the climate of Central Africa and its variability has been the subject of very few studies. 203 The few existing studies suggest that there is not a significant relationship between ENSO and 204 precipitation in Central Africa (Philippon et al., 2012; Taylor et al., 2013b). ENSO has also been 205 linked to the devastating droughts of the 1970s and 1980s in the Sahel (e.g. Giannini et al., 206 2003). Drier (wetter) decades in the Sahel are usually correlated with El Niño (La Niña) events 207 (e.g. Nicholson and Selato, 2000; Janicot et al., 2011). Several different ENSO indices have 208 developed over time, but the Multivariate ENSO Index (MEI) is favored over other indices 209 because it combines the significant features of all observed surface fields in the tropical Pacific. 210 MEI monthly values were obtained from the NOAA Earth System Research Laboratory (NOAA, 211 2017).

The PDO is often described as a long-lived El Niño-like pattern of Pacific climate variability (Zhang et al. 1997). The PDO index is based upon patterns of variation in sea surface temperature of the North Pacific Ocean with warm and cold phases that can persist for 20-30 years. Unlike ENSO, the PDO is not a single physical mode of ocean variability, but rather the sum of several processes with different dynamic origins. The PDO monthly values were obtained from the NOAA Earth System Research Laboratory database (NOAA, 2017).

The NAO represents a north-south oscillation atmospheric mass between the Icelandic lowpressure system and the Azores high-pressure system. The positive phase of the NAO reflects below-normal surface pressure over the Icelandic to Arctic regions and above-normal surface

221 pressure over the subtropical Atlantic. The negative phase reflects the opposite. The NAO 222 exhibits considerable interseasonal, interannual and multidecadal variability with irregular 1- to 223 24-year cycles (Hurrell 1995, Chelliah and Bell 2005), but has a dominant quasiperiod 224 oscillation of 3 to 6 years and a less significant 8 to 10 year mode (Hurrell et al. 2003). The NAO 225 is among the known modes of natural variability influencing North Africa precipitation on a 226 variety of time-scales, especially in winter and early spring. Drier (wetter) decades in North 227 Africa largely correspond to positive (negative) NAO phase (Lopez-Moreno et al., 2011). 228 Correlations are however particularly stronger for negative NAO phases (Donat et al., 2014). For 229 example, the negative phase of the NAO from the mid-1950s to late 1970s indicates relatively 230 wet conditions with a gradual shift towards drier conditions in the early 1970s. Recent years have 231 also been considered wetter. NAO monthly values were obtained from the NOAA Earth System 232 Research Laboratory database (NOAA, 2017).

233 The AMO is an index of sea surface temperature over the North Atlantic Ocean (quasi-period 234 cycles of roughly 50 to 70 years) with negative and positive phases that may last for 20-40 years 235 each and lead to differences of about 15°C between extremes. Paleoclimatologic studies have 236 confirmed that these changes have been occurring over the past 8000 years (Knudsen et al., 237 2011). The AMO was in positive phases from 1860 to 1880 and 1930 to 1960, and in negative 238 phases from 1905 to 1925 and 1970 to 1990. The AMO flipped to a positive phase in the mid-239 1990s and it is believed that the AMO is gradually moving to a negative phase (McCarthy et al., 240 2015). Higher rainfall over the Sahel is associated to positive phases of the AMO (Diatta and 241 Fink, 2014), while the opposite occurs in the Gulf of Guinea (Mohino et al., 2011). The AMO 242 monthly values were obtained from the NOAA Earth System Research Laboratory database 243 (NOAA, 2017).

244 The interaction of climate variability modes can enhance or diminish certain climatic forcings on 245 local hydrologic processes (Hanson et al. 2004). When El Niño (La Niña) occurs with the warm 246 (cold) PDO phase, rainfall tends to increase over the Sahara to the Gulf of Guinea and Southern 247 Africa, while the opposite occurs in the Horn of Africa (Wang et al., 2014). Several studies 248 suggest that the AMO modulates the ENSO and NAO variability (Dong et al. 2006; Dong and 249 Sutton 2007; Timmermann et al. 2007; Zhang et al., 2012; García-García and Ummenhofer, 250 2015). Strengthened (weakened) La Niña effects coincide with a positive (negative) phase of the 251 AMO (Geng et al., 2016). In the Sahel (Lake Chad), the severe impact of droughts of the 1970s 252 and 1980s are tied to the combined effect of the negative phase of the AMO and El Niño events 253 (Okonkwo et al., 2015). Finally, ENSO and AMO are well-known climate teleconnections that 254 have been associated with extreme rainfall variability in Western/Central Africa (Ndehedehe et 255 al., 2017). An inverse relationship exists between the AMO and the NAO decadal tendencies. 256 When the AMO is negative, NAO tends more often to the positive state. Statistical analyses over the 20th century suggest that the AMO precedes NAO by 10-15 years (Peings and Magnusdottir, 257 258 2014). These findings provide an interesting possibility of decadal forecasting.

259

3. Methods

3.1. GRACE observations

There has been great interest in the use of GRACE satellites to monitor changes in water storage, especially in regions with limited ground-based data such as Africa (Henry et al., 2011; Ramilien et al., 2014; Richey et al., 2015; Chen et al., 2016; Hassan and Jin, 2016; Rateb et al., 2017). GRACE satellites provide a spatially filtered image of real TWS that needs to be processed to

266 produce information on changes in TWS. There are generally three approaches to process 267 GRACE total water storage change signals: the scaling factor approach, the additive correction 268 approach and the multiplicative correction approach. The validation of GRACE-based estimates 269 is challenging because results can differ by up to 100% depending on which processing approach 270 is used, in particular over i) (semi-)arid areas, ii) areas with intensive irrigation, and iii) relative small basins (i.e. $\leq 200,000 \text{ km}^2$) for which the additive correction approach may be more 271 272 appropriate (Long et al., 2015). It is thus imperative to compare GRACE-based estimates with 273 ground-based data to assess their validity.

274 Considering that most of the studied aquifer systems are located in arid and semi-arid areas, the 275 additive correction approach as presented by Longuevergne et al. (2010) to provide total water 276 storage estimates from 2002-2013 at a monthly basis has been used. This is based upon monthly 277 spherical harmonic (SH) gravity field solutions R05 monthly data from CSR (Center for Space 278 Research, Univ. of Texas at Austin, US), truncated at degree and order 60 (Bettadpur, 2007), 279 including a destriping filter (Swenson and Wahr, 2006) and additional 300 km Gaussian 280 smoothing. Alternate methods for leakage corrections encompass the mascon-type approach. The 281 basic difference between spherical harmonics (SH) and mascons is that SH solutions are global 282 whereas mascons can be applied at regional to global scales. A recent study has shown that 283 although long-term trends for SH are lower than those for mascons, they remain highly 284 correlated (Scanlon et al., 2016). The method used for detrending total water storage time series 285 is fitting and removing a trend model consisting of a long-term linear and seasonal cycles by 286 using linear regression (Sun et al., 2017). Results are compared with groundwater changes from 287 piezometry ($\Delta GWS_{OBSERVED}$) and modeled changes in total water storage (ΔTWS_{MODEL}) in order 288 to identify any long-term covariance. Particular attention is given to aquifer systems whose area is below the limit of the GRACE footprint (Karoo Sedimentary, Stampriet TransboundaryAquifer System and Volta Basin Aquifer).

291

292

3.2. A modelling approach to extend the GRACE timeframe

293 Trends during the GRACE era (2002 - 2017) are dominated by internal climate variability (i.e., 294 arising from interactions and chaotic variability within the climate system, particularly in 295 rainfall) rather than by the forced response (i.e., driven primarily by human induced changes in 296 atmospheric composition) (Fasullo et al., 2016). Key to understanding reported changes during 297 the GRACE record is quantifying the character of internal climate modes. The GRACE era only 298 covers a very limited number of climatic oscillation cycles as some modes like the AMO, PDO, 299 and NAO have oscillation periods longer than the GRACE observation record. Several studies 300 indicate that low-frequency cycles like AMO and PDO are particularly influential in modulating 301 high-frequency cycles such as ENSO. To bridge this gap, there is a need to extend the GRACE 302 timeframe to the "past" using a model that is able to reconstruct the interannual to decadal 303 climate-driven changes in water storage. A climate-driven model to estimate long-term water 304 storage dynamics, independent from GRACE data, was developed and applied at the aquifer 305 scale.

According to MacDonald et al. (2012), groundwater development stress is relatively low in most of the large African aquifers with renewable groundwater resources. This suggests that changes in groundwater storage in such aquifers tend to be dominated by climatic variations. For that reason, human influences (such as abstraction and land-use changes) are neglected in the simple simulation model. This model is based on elaboration of the general water balance equation:

311
$$\frac{d\text{TWS}}{dt} = P - E - R \qquad (\text{Eq. 1})$$

312 where P is precipitation, E is actual evapotranspiration, R is runoff (or discharge at the basin 313 outlet), and TWS is total water storage (sum of water stored in vegetation, ice, snow, lakes and 314 streams, soil moisture and groundwater). All components are given in millimetres per month. 315 Mean precipitation and actual evapotranspiration were computed by averaging data available 316 from global datasets with spatial resolutions of 0.5° x 0.5° at aquifer scale from 1982 to 2011 317 (Global Precipitation Climatology Centre dataset for precipitation (Becker et al., 2013), and Max 318 Planck Institute dataset for actual evapotranspiration) (Jung et al., 2010). These datasets were 319 selected because of their capability to capture the regionally averaged seasonal cycles (Mueller et 320 al., 2011; Sun et al., 2018).

321 Integration of Eq. 1 gives:

322

$$\Delta TWS = \int Pdt - \int Edt - \int Rdt \qquad (Eq. 2)$$

323 ΔTWS is the change of total water storage over the time interval of integration, thus it includes 324 the changes in water stored in vegetation, snow, ice, lakes and streams, soil moisture and 325 groundwater. Integration over time of P, E, and R will generate a long-term trend in ΔTWS , 326 which is attributed to integration of systematic errors in these variables. Unbiased datasets are 327 therefore required. Considering that P is the dominant factor controlling long-term variations of 328 E, and R, it is assumed that runoff is constant over time, i.e. contribution to storage as a linear 329 trend (Bouwer et al., 2006; Liu et al., 2013). By doing so, when estimating storage changes by 330 integration of *R*, a long-term trend related to runoff is removed. Thus, Eq. 2 becomes:

331
$$\Delta TWS_{MODEL} = \int Pdt - \int Edt - \int Rdt \approx detrend(\int Pdt - \int Edt)$$
(Eq. 3)

In absence of detailed field data on all these storage components it is difficult to isolate the change in groundwater storage (Δ GWS), but under certain circumstances – to be judged by the modeller– it is plausible that Δ GWS is nearly equal to Δ TWS_{MODEL}. Such circumstances may, for instance, apply to relatively long integration intervals (several years) in arid and semi-arid regions where the assumed combined non-groundwater storage capacity is small compared to the simulated change in total water storage (Δ TWS_{MODEL}).

338

339 3.3. Ground-based measurements

340 Due to the general lack of continuous long-term groundwater level data, the selection of records 341 for the validation of GRACE-based estimates was done based on the limited data available in 342 literature and their representativeness. The selected records are usually located no farther than 20 343 km from surface water bodies (e.g. river, lake, oued) and tap shallow unconfined aquifers. The 344 records provide groundwater levels at a monthly basis for different periods ranging from 5 to 20 345 years (Figure 2 and Table 2). In order to compare piezometry with total water storage, long-term 346 groundwater level data were detrended by using the MATLAB function detrend that substracts 347 the mean or a best-fit line (in the least-square sense) from data. If the data do have a trend, 348 detrending forces the mean to zero and reduces overall variation.

349	INSERT TABLE 2 HERE
350	INSERT FIGURE 2 HERE
351	

352 3.4. Wavelet analysis

353 Wavelet transforms to analyze teleconnections between groundwater level, GRACE-based 354 estimates, climate-driven model and climate indices time series were used both in amplitude and 355 frequency. A MATLAB script developed by Grinsted et al. (2004) that enables doing continuous 356 wavelet transform (CWT), cross wavelet transform (XWT) and wavelet coherence (WTC) plots 357 was applied. CWT expands the time series into time frequency space, XWT finds regions in time 358 frequency space where the time series show high common power and WTC finds regions in time 359 frequency space where the two time series co-vary (but does not necessarily have high power) 360 (Torrence and Compo, 1998; Labat et al., 2000; Grinsted et al., 2004; Labat 2005; 2008; Holman 361 et al., 2011). Although the three methodological steps described previously were necessarily 362 followed, the presentation of the results and discussion focuses on the WTC plots. High 363 correlation between time series is indicated by light yellow zones. The arrows \rightarrow and \leftarrow in zones 364 of the WTC figures indicate the positive (in-phase) and negative (anti-phase) relationships 365 between two time-series, respectively. Meanwhile, the arrows \downarrow and \uparrow show that time series 1 366 lags time series 2 by 90° . The interpretation of lags in these zones can be however challenging 367 and should be done carefully as a lead of 90° can also be interpreted as a lag of 270° or a lag of 368 90° relative to the anti-phase (opposite sign). A good indication to support that there is a 369 connection and link between times series is that the phase-arrows generally point only in one 370 direction for a given wavelength.

371

372 **4. Results and discussion**

373 4.1. Evaluation of GRACE-based and climate-driven model estimates

374 GRACE-based and climate-driven model total water storage changes (ΔTWS_{GRACE} and 375 ΔTWS_{MODEL} , respectively) are compared to groundwater levels in the studied aquifers to assess 376 to what extent they covary with $\Delta GWS_{OBSERVED}$. All data were detrended in order to focus the 377 analysis on the fluctuations in the data. However, it is worth mentioning that total water storage 378 time series are nonlinear, nonstationary and tend to vary at multiple temporal scales, making 379 filtering and detrending of total water storage a nontrivial task (Sun et al., 2017). The data 380 were further normalized based on the mean and standard deviation of each dataset in order to 381 provide a benchmark and comparison basis. Results suggest that changes in total water storage 382 estimates describe generally well groundwater-level dynamics (Figure 3). These results are 383 further verified by wavelet transform analysis that indicate that there exists a high correlation 384 between GRACE-based and climate-driven model water storage estimates and groundwater level 385 both at intra-annual and inter-annual scale (Figure 4a and Figure 4b). Given that comparison is 386 done with groundwater level records from shallow boreholes that are located in the vicinity of 387 surface water bodies (usually <20 km) which are likely to have a strong surface water / 388 groundwater interaction, it is fair to conclude that ΔTWS_{GRACE} , ΔTWS_{MODEL} and 389 $\Delta GWS_{OBSERVED}$ representative of groundwater fluctuations in shallow unconfined aquifers are 390 strongly correlated. This could also suggest that storage changes in deep aquifers are limited, 391 thus supporting the assumptions that they are not being actively recharged and that they are 392 exploited still largely at low rates. The near-synchronous signals of groundwater levels and the 393 climate-driven model water storage estimates (Figure 3, Figure 4a and Figure 4b) reveal that 394 shallow aquifers are highly responsive to rainfall temporal patterns, and reinforce the concept 395 that natural climate variability, in particular changes in precipitation, considerably contributes to 396 groundwater storage changes.

397	INSERT FIGURE 3 HERE
398	INSERT FIGURE 4a HERE
399	INSERT FIGURE 4b HERE

400

401 Results of the model allowed identifying four different types of groundwater storage dynamics 402 that are largely correlated with African climate zones. The model indicates that the North-403 Western Sahara Aquifer System (NWSAS) located in Northern Africa had a decrease in storage 404 from early-1980s to late-1980s, an increase in early 1990s followed by a decrease from mid-405 1990s to mid-2000s, an increase in mid-2000s, and a decrease since then (Figure 5). This is in 406 relatively good agreement with rainfall pattern and shallow groundwater fluctuation in the 407 vicinity of oueds in the Ouargla Plain in Algeria/Tunisia (Bellaoueur, 2008) and central Tunisia 408 (Massuel and Riaux, 2017) (Figure 2). The model's water storage increase in mid-2000s also 409 supports the assumption that the shallow aquifers (including outcrops of the deep aquifers) of the 410 North-Western Sahara Aquifer System are receiving a fraction of modern water as recharge from 411 infiltration of rainfall coming from the Sahara Atlas Mountains in Algeria and the Dahar and 412 Nafusa Mountains in Tunisia and Lybia (Baba-Sy, 2005; Al-Gamal, 2011). It should be noted 413 however that groundwater abstraction in the NWSAS has steeply risen over the past decades 414 because of tapping confined aquifers by drilling deep boreholes in the 1980s for water supply 415 and irrigation schemes (OSS, 2003). These boreholes have had very little maintenance since they 416 were drilled and recently observed water table rises in shallow aquifers could be locally 417 influenced by upward leakage through corroded borehole casing (Messekher et al., 2012).

INSERT FIGURE 5 HERE

419 The aquifers located in the Sahel (Nubian Sandstone Aquifer System, Lake Chad Basin, Irhazer-420 Iullemmeden Basin, and Senegalo-Mauritanian Basin) have a similar multi-decadal behavior, 421 which is characterized by a significant decrease in groundwater storage from early-1980s to mid-422 1990s followed by a partial recovery (Figure 6). As rainfall in the Sahel has generally increased 423 since mid-1990s, this result proves to be in good agreement with the observations from 424 piezometry indicating that the water table has risen since the mid-1980s in large parts of the 425 central Sahel (Favreau et al., 2009, 2012). It also supports the assumption that rainfall infiltration 426 is a primary source of recharge, though recharge from surface water bodies such as the Niger and 427 the Nile Rivers is non-negligible and limited to the vicinities of the rivers (perennial and 428 seasonal) and endoreic ponds (Nazoumou et al., 2015; Ngounou-Ngatcha et al., 2015). Aquifers 429 located in the tropics (Volta Basin and Karoo Carbonate) show an opposite behavior although 430 changes are not as pronounced as in the aquifers in the Sahel (Figure 7). This result is in line 431 with recent observations that indicate a drying trend in central equatorial Africa (west of 432 Albertine Rift) (Diem et al., 2014) and over Guinea regions, such as Benin and Nigeria (Bamba 433 et al., 2015).

434

INSERT FIGURE 6 HERE

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INSERT FIGURE 7 HERE

Contrary to the aquifers in the Sahel, the aquifers in Southern Africa do not show a particular
multi-decadal pattern, but rather a strong inter-annual pattern. The model indicates a decrease in
storage from early-1980s to late-1980s, an increase in late-1980s/early-1990s, a decrease from

early-1990s to mid-1990s/late-1990s, an increase in late-1990s/early-2000s, a decrease from
early-2000s to mid-2000s, and an increase since mid-2000s (Figure 8). This result is consistent
with studies that revealed that long-term rainfall trends in Southern Africa are weak but exhibit
an increased variability since 1970 (Richard et al., 2001).

443

INSERT FIGURE 8 HERE

444 *4.2. Groundwater storage variability and its association with climate teleconnections*

445 Groundwater storage variability and its association with climate teleconnections is studied by 446 applying wavelet transforms between simulated changes in total water storage (ΔTWS_{MODEL}) 447 and climate indices (NAO, ENSO, and AMO). In Northern Africa, groundwater storage appears 448 to be correlated to NAO (Figure 5c). WTC reveals three regions with high coherence (good 449 correlation), i.e. 6-8 year band from 1990 to 1995 (Box 1 in Figure 5c), 1-2 year band from mid-450 1990s to mid-2000s (Box 2 in Figure 5c), and 2-3 year band from mid-2000s onwards (Box 3 in 451 Figure 5c), which indicates that NAO exerts an influence on changes in groundwater storage. 452 Positive (negative) NAO phase largely correspond to decreasing (increasing) groundwater 453 storage. The results confirm that inter-annual correlations tend to be stronger for negative NAO 454 phases (Box 2 and Box 3 in Figure 5c). This has been particularly true since the AMO shift back 455 to a positive phase in mid-1990s, thus suggesting that the AMO exerts a low-frequency 456 modulating influence on groundwater storage changes.

The influence of the AMO on groundwater storage appears to be much more direct in the Sahel.
The AMO appears to exert a multi-decadal influence as a positive (negative) phase largely
corresponds to increasing (decreasing) aquifer storage (Figure 6). For instance, all aquifers in the

460 Sahel show a significant modeled decrease in aquifer storage during a negative phase of the 461 AMO from the early-1980s to mid-1990s followed by an increase in groundwater storage during 462 a positive phase of the AMO since the mid-1990s. Mega-droughts in the Sahel are considered to 463 be linked to the combined effect of the negative phase of the AMO and El Niño events 464 (Shanahan et al., 2009; Masih et al., 2014). Such combination also appears to have a substantial 465 adverse effect on groundwater storage as it could potentially result, depending on recharge 466 processes in play, in both reduced recharge to the aquifers and in water level declines attributed 467 to climate-induced pumping (Gurdak 2017; Russo and Lall 2017). The AMO exerts an opposite 468 influence in the aquifers located in the tropics (Volta Basin and Karoo Carbonate), as positive 469 (negative) phase largely corresponds to (increasing) decreasing groundwater storage (Figure 7). 470 Total water storage and consequently groundwater storage inter-annual variability both in the 471 Sahel and in Equatorial Africa are likely to be impacted by ENSO, as WTC plots for the Nubian 472 Sandstone Aquifer System and the Senegalo-Mauritanian Basin (Figure 9) and for the Volta 473 Basin and Karoo Carbonate Aquifers (Figure 10) reveal several regions with high coherence 474 (good correlation). These regions largely coincide with El Niño events (1982-1983, 1986-1988, 475 1991-1992, and 1997-1998) and La Niña events (1998-2000). A recent study by Siam and Eltahir 476 (2017) revealed a strong correlation between ENSO, rainfall and flow in the Nile basin. El Niño 477 years usually lead to drought conditions, whereas La Niña years are more flood-prone. 478 Considering that recharge of the shallow aquifers mainly occurs by rainfall infiltration and 479 river/surface water interaction, it could be assumed that El Niño (La Niña) years could lead to 480 decreased (increased) groundwater storage. This assumption could be extended to the Sahel 481 and/or Equatorial Africa as similar observations have been found for Lake Chad (Okonkwo et 482 al., 2015), the Senegal and Niger River basins (Diaw et al., 2012; Nazoumou et al., 2015), and

483 Lake Volta (Owusu et al., 2008). Due to the relative shortage of long-term climate data, any 484 assumption on cause-effect relationship in the correlation results of the model and climate 485 indices in Central Africa is particularly more complex as there has been only a very limited 486 number of studies of the climate of this region (Philippon et al., 2012). Central Africa has the 487 lowest gauge density in sub-Saharan Africa (Washington et al., 2013) and has seen a dramatic 488 decline in the number of rain gauges, especially after 1980s (Asefi-Najafabady and Saatchi, 489 2013, Zhou et al., 2014). Studies diverge in their conclusions in this region. According to Gao et 490 al. (2016), drier conditions are associated with El Niño events while Taylor et al. (2013) suggest 491 that the influence of ENSO varies spatially and studies in has indicated an opposite pattern as El 492 Niño years are associated to increases in recharge generated by heavy rainfall (Taylor et al., 493 2013).

494

INSERT FIGURE 9 HERE

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INSERT FIGURE 10 HERE

496 WTC plots for the Stampriet Transboundary Aquifer System and the Karoo Sedimentary Aquifer 497 in Southern Africa also reveal important correlation between groundwater storage and ENSO 498 events with El Niño (La Niña) events usually leading to drier (wetter) conditions and decreasing 499 (increasing) water levels (Figure 8). The dynamics of these aquifers are not similar and thus 500 indicates that other climate modes might also be exerting an influence in Southern Africa. 501 Previous studies present clear evidence of the importance of the Indian Ocean Dipole (IOD) 502 index in modulating rainfall variability in Eastern Africa (Taylor et al., 2013b). The IOD has traditionally been linked to ENSO (Marchant et al., 2006; Fan and Liu, 2017). Major ENSO 503 504 warm (El Niño) events combined with a positive phase of the IOD have led to wet extremes and significant recharge in the Karoo Sedimentary Aquifer (Figure 11). Conclusions about the correlation between the IOD and groundwater storage changes for the Nubian Aquifer Sandstone System and the Karoo Carbonate Aquifer are more challenging because the influence of IOD varies across the aquifer basin (Awange et al., 2014; Onyutha and Willems, 2017) and because of the lack of data, respectively.

510

INSERT FIGURE 11 HERE

511

512 **5.** Conclusions

513 A two-variables climate-driven model using precipitation and actual evapotranspiration data 514 from global datasets was developed to reconstruct past total water storage changes in Africa from 515 1982 to 2011. Although the model has the important limitation of not considering human 516 influences such as abstraction, land-use changes, and dam management, it offers robust pointers 517 to assess the monthly dynamics of groundwater storage at very little computational cost as 518 model-based total water storage changes ΔTWS_{MODEL} and observed groundwater storage 519 changes $\Delta GWS_{OBSERVED}$ (representative of shallow groundwater fluctuations) are strongly 520 correlated. GRACE-based ΔTWS_{GRACE} estimates are also highly correlated with model-based 521 ΔTWS_{MODEL} and $\Delta GWS_{OBSERVED}$. As GRACE Follow-On (GRACE-FO) mission is scheduled to 522 be launched in early 2018, ΔTWS_{GRACE} estimates will thus prove to be a well-founded tool to 523 provide a general overview at basin scale of groundwater storage changes that are associated to 524 shallow groundwater fluctuations and that are likely to have a strong interaction with surface water. The near-synchronous signals of groundwater levels, GRACE and the climate-driven
 model estimates reveal that shallow aquifers are highly responsive to rainfall temporal patterns.

527 Obtained results indicate that recharge from rainfall patterns associated to NAO and ENSO are 528 the main drivers of inter-annual groundwater storage changes in Northern Africa and Sub-529 Saharan Africa, respectively. The AMO plays a significant role in decadal to multi-decadal 530 variability, particularly in the Sahel as positive (negative) AMO phase largely corresponds to 531 increasing (decreasing) groundwater storage. The AMO has been in a positive phase since mid-532 1990s and as a result, this has contributed to a water table rise in large parts of the Sahel. A 533 change of phase could have an overwhelming impact on surface-water and groundwater 534 resources, as mega-droughts in the early 1980s in the Sahel are tied to the combined effect of a 535 negative phase of the AMO and a positive phase of the ENSO. These devastating droughts could 536 trigger significant groundwater storage changes, resulting in reduced recharge to the shallow 537 aquifers and water level declines attributed to climate-induced pumping from dug-wells and 538 shallow boreholes.

539 The findings of this study could be beneficial to decision-makers and help to adequately prepare 540 effective climate variability and change adaptation plans both at national and transboundary 541 level. National groundwater governance frameworks in Africa usually need either reviewing and 542 upgrading water laws and policies or completing water law with regulations (FAO, 2015). 543 Integrating climate variability aspects into water laws and policies (e.g. drought and flood 544 management plans, provisions for Managed Aquifer Recharge (MAR) schemes), strengthening 545 national meteorological, hydrological and groundwater-monitoring networks, and in particular 546 strengthening links between water decision-makers and meteorological institutions are crucial 547 measures for improving groundwater governance with special reference to climate change.

548 Integrated Water Resources Management (IWRM) is now widely accepted by water decision-549 makers as the way forward for efficient, equitable and sustainable development and management 550 of the world's limited water resources and for coping with conflicting demands (UNESCO, 551 2009). IWRM structures in Africa are rolled out across the continent with the present focus on 552 the establishment of river basin / catchment organizations at national and transboundary level. 553 However, groundwater is still poorly integrated into these organizations' IWRM and climate 554 adaptation plans. MAR is a promising adaptation approach to reduce vulnerability to climate 555 variability and aquifer over-exploitation. Findings from this study illustrate that MAR operations 556 might take advantage of temporal patterns in precipitation to enhance recharge during the 557 corresponding wet phases of ENSO, NAO, and AMO. Institutions in charge of the management 558 of groundwater resources at national and transboundary level, as well as river basin / catchment 559 organizations, should strengthen their support to MAR programs and initiatives to incentivize 560 local water managers to store excess renewable water in aquifers during wet periods which can 561 be used to off-set limited surface-water supplies during dry periods. The findings suggest that 562 preferred periods for artificial recharge are negative phases of the NAO in Northern Africa, 563 positive phases of the AMO in the Sahel, and La Niña years in Southern Africa. Finally, it is 564 worth emphasizing that developing long-term effective and reliable strategies for coping with 565 water scarcity threats and climate variability and change will also have to overcome the fact that 566 there are still large uncertainties and limited adequate data for decision-making. In this regard, it 567 is also important to undertake joint actions in data collection interpretation and reporting as a 568 means to promote inter-basin/inter-aquifer collaboration, to harmonise strategies and promote 569 exchange of experiences.

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986 Appendix: Acronyms and abbreviations

TWS	Total water storage		
ΔGWS	Groundwater storage changes		
$\Delta GWS_{OBSERVED}$	Observed groundwater storage changes		
ΔTWS	Total water storage changes		
ΔTWS_{GRACE}	GRACE-based changes in total water storage		
ΔTWS_{MODEL}	Simulated changes in total water storage		
AMO	Atlantic Multidecadal Oscillation		
CWT	Continuous wavelet transform		
ENSO	El Niño Southern Oscillation		
GRACE	Gravity Recovery And Climate Experiment		
IOD	Indian Ocean Dipole		
ITTAS	Iullemmeden, Taoudeni/Tanezrouft Aquifer System		
IWRM	Integrated Water Resources Management		
MAR	Managed Aquifer Recharge		
MEI	Multivariate ENSO Index		
NAO	North Atlantic Oscillation		
NSAS	Nubian Sandstone Aquifer System		
NWSAS	SAS North-Western Sahara Aquifer System		
PDO	Pacific Decadal Oscillation		
STAS	Stampriet Transboundary Aquifer System		
WTC	Wavelet coherence		
XWT	Cross wavelet transform		

Table 1 – Basic hydrogeological, socio-economic and governance overview of the studied aquifers

Aquifer	Aquifer	Zone	Population	Approx.	Rainfall	Aquifer type	Institutional
No. (Fig. 1)			(approx. no. of	area (km²)	(mm/year)		arrangement
			inhabitants)				
1	North-Western	Northern Africa	4,000,000	1,300,000	10-300	Sand, sandstone,	Observatory of
	Sahara					sandy clay,	the Sahara and
	Aquifer					calcareous, dolomite	the Sahel (OSS)
	System						
	(NWSAS)		(7.000.000	2 000 000	1.550		T • <i>i</i> A <i>i</i> 1 • <i>i</i>
2	Nubian Sandatana	Northern Africa	67,000,000	2,800,000	1-550	Nubian and Post-	Joint Authority
	Aquifor					Nubian	
	System						
	(NSAS)						
3	Senegalo-	Sahel	12,000,000	330,000	20-1,850	Ouaternary -	Senegal River
	Mauritanian		, ,	,	,	Maestrichtien	Basin
	Basin						Development
							Authority
							(potential)
4	Irhazer-	Sahara-Sahel	13,000,000	580,000	80-900	Sedimentary deposit	Consultation
	Iulluemmeden					including Terminal	mechanism to
	Basin					Continental and	be
						Continental	operationalized
						(Cretaceous –	
						(Cretaceous – Tertiary)	
5	Lake Chad	Sahara-Sahel	22,000,000	2,300,000	40-1,400	Sedimentary: Upper	Lake Chad
	Basin		, ,	, ,	,	Quaternary, lower	Basin
						Pliocene and	Commission
						Continental	(potential)
						Terminal (Tertiary)	
6	Volta Basin	Tropical/Equatorial	14,000,000	145,000	500-1,100	Sedimentary rocks	Volta Basin
		Africa					Authority
_	17		10.000.000	(00.000	1.000	T · · · · 1 ·	(potential)
7	Karoo-	Equatorial Africa	10,000,000	600,000	1,000-	Limestone/sandstone	International
	Cardonate				1,800		the Congo
							Oubangui-
							Sangha
							Basin (potential)
8	Stampriet	Southern Africa	50,000	90,000	200-350	Kalahari group	Orange-Senqu
	Transboundary					aquifers and Karoo	River
	Aquifer					supergroup aquifers	Commission
	System						
9	Karoo	Southern Africa	6,000,000	170,000	350-1,200	Consolidated	Orange-Senqu
	Sedimentary					sedimentary rocks	River
							Commission
							(potential)

Aquifer	Aquifer	Groundwater-	Well/Borehole depth	Source
No.		level time frame	_	
1	North-Western Sahara Aquifer	1982-2011	Shallow piezometer	Massuel and Riaux,
	System (NWSAS)		(located near the	2017
			boundaries of the	
			aquifer)	
2	Nubian Sandstone Aquifer System	1998-2004	Shallow piezometer	El Shazli, 2018
	(NSAS)		(vicinity of Lake	
		Nasser)		
3	Senegalo-Mauritanian Basin	1997-2002	Shallow piezometer	Gning et al., 2015
			(vicinity of Senegal	
			River)	
4	Irhazer-Iullemmeden Basin	1991-2015	<75m	Updated from
			(<75km from the	Favreau et al., 2009
			Niger River)	
5	Lake Chad Basin	2006-2011	85m	Vasollo, 2017
			(Maiduguri - vicinity	
			of Lake Chad)	
6	Volta Basin	2006-2011	Shallow piezometer	Lutz et al., 2015
7	Karoo-Carbonate	N/A	N/A	N/A
8	Stampriet Transboundary Aquifer	1986-2008	Shallow piezometer	UNESCO, 2016
	System		(<50m)	
9	Karoo Sedimentary	1994-1999	Shallow piezometer	IGRAC, 2017
			(<10m)	

Table 2 – Ground-based measurements in the studied aquifers

N/A : not applicable

FIGURE CAPTIONS:



Figure 1 – Location of the studied aquifers in Africa



Figure 2 – Groundwater level fluctuation in the studied aquifers



Figure 3 – Normalized observed groundwater $\Delta GWS_{OBSERVED}$ (red), GRACE-based ΔTWS_{GRACE} (blue) and model-based total water storage variability ΔTWS_{MODEL} (green) in the studied acuifers

Figure 4 – Wavelet coherence (WTC) plots in the studied aquifers: **a** Northern Africa and Sahara-Sahel, and **b** Tropical/Equatorial Africa and Southern Africa (Note: x-axis is date (year) and y-axis is period in years. Correlation coefficients vary from 0 (dark blue) to 1(light yellow))

a		Groundwater level / GRACE	Groundwater level / Model	GRACE / Model
1	North-Western Sahara Aquifer System	1 2 2003 2012	1 8 1985 2010	1 2 2003 2012
2	Nubian Sandstone Aquifer System	N/A	1 2 1999 2004	1 2 2003 2012
3	Lake Chad Basin	1 2007 2011	1 2007 2011	1 2 2003 2012
4	Irhazer-Illuemeden Basin	1 2 2004 2012	1 4 1995 2010	1 2 2003 2012

5	Senegalo- Mauretanian Basin	N/A	1 1998 2003	1 2 2003 2012
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9	Karoo Sedimentary	N/A	1 2 1995 1999	1 2 2003 2012

Figure 5 – Groundwater storage variability and its association with climate teleconnections in Northern Africa (1982-2011): **a** Northern Atlantic Oscillation (NAO) and Atlantic Multi-Decadal Oscillation (AMO) indices, **b** simulated changes in total water storage (ΔTWS_{MODEL}), and **c** ΔTWS_{MODEL} -NAO wavelet coherence plot (see text for description of boxes 1, 2 and 3) (Note: x-axis is date (year) and y-axis in **c** is period in years)



Figure 6 – Groundwater storage variability and its association with climate teleconnections in the Sahel (1982-2011): **a** Atlantic Multi-Decadal Oscillation (AMO) index and **b** simulated changes in total water storage (ΔTWS_{MODEL})



Figure 7 – Groundwater storage variability and its association with climate teleconnections in Equatorial Africa (1982-2011): **a** Atlantic Multi-Decadal Oscillation (AMO) index and **b** simulated changes in total water storage (ΔTWS_{MODEL})



Figure 8 – Groundwater storage variability and its association with climate teleconnections in Southern Africa (1982-2011): **a** El Niño Southern Oscillation (ENSO) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL} -ENSO wavelet coherence plots for the **c** Karoo Sedimentary Aquifer and **d** Stampriet Transboundary Aquifer System (Note: x-axis is date (year) and y-axis in **c** and **d** is period in years)

Figure 9 - Groundwater storage variability and its association with climate teleconnections in the Sahel (1982-2011): **a** El Niño Southern Oscillation (ENSO) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL} -ENSO wavelet coherence plots for the **c** Nubian Sandstone Aquifer System and **d** Senegalo-Mauritanian Basin Aquifer (Note: x-axis is date (year) and y-axis in **c** and **d** is period in years)

Figure 10 – Groundwater storage variability and its association with climate teleconnections in Equatorial Africa (1982-2011): **a** El Niño Southern Oscillation (ENSO) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL} -ENSO wavelet coherence plots for the **c** Volta Basin Aquifer and **d** Karoo Carbonate Aquifer

(Note: x-axis is date (year) and y-axis in **c** and **d** is period in years)

Figure 11 – Groundwater storage variability and its association with the Indian Ocean Dipole (IOD) index in Eastern Africa (1982-2011): **a** Indian Ocean Dipole (IOD) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL} -IOD wavelet coherence plots for the **c** Nubian Sandstone Aquifer System, **d** Karoo Carbonate Aquifer and **e** Karoo Sedimentary Aquifer

(Note: x-axis is date (year) and y-axis in **c**, **d** and **e** is period in years)

