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Abstract

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

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This article is part of the topical collection “Determining groundwater sustainability from long-term piezometry in Sub-Saharan Africa”

1. Introduction

Africa faces major water resources management challenges, largely because water is unevenly distributed over the continent and over time. About 64% of the population rely on limited and highly variable amounts of water, and 25% of the population experience difficulties in water use due to accessibility or mobilizations issues (e.g. water infrastructure, flow controls, costs) (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 and Bierkens, 2014), which may compromise the future livelihoods of millions of people and their living standards. Global climate change and variability is expected to exacerbate this issue as it will bring more extreme climate conditions such as droughts (Prudhomme et al., 2014; Trenberth et al., 2014; Malherbe et al., 2016). Groundwater plays an important role in society’s adaptation to climate change and variability, especially because it is more resilient to the effects of climate change than surface water (Green et al., 2011; Treidel et al., 2012; Van der Gun, 2012; Taylor et al., 2013a). Groundwater’s unique buffer capacity provides a major strength to reduce the risk of temporary water shortage, and to create conditions for survival in areas were climate change is expected to cause water stress (Falkenmark, 2013).

An estimated 75% or more of Africans use groundwater as their main source of drinking water (UNEP, 2010), particularly in rural areas that rely on low-cost dug wells and boreholes. There is very limited reliable and comprehensive statistics on groundwater use in Africa, but previous 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 many parts of the world (Famiglietti, 2014; Konikow 2015) including Asia where 14% of 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, 2015). In contrast to other regions in the world such as Western Mexico, the High Plains in the central U.S., the Middle East, North-East Pakistan, North-West India, and North-East China, most of Sub-Saharan Africa has not yet experienced the "groundwater crisis" (Famiglietti, 2014) caused by the widespread over-abstraction of groundwater to support large-scale agriculture. Moreover, some major African aquifers tend to coincide with areas of relatively lower population density and water demand (e.g. the Sahel aquifer Basins, the Congo Basin in Central Africa, and the Kalahari Basins in Southern Africa) (Foster et al., 2006; Wada et al., 2010; Gleeson et al., 2012; MacDonald et al., 2012). Many African countries and/or joint bodies in charge of implementing transboundary water agreements thus have an opportunity to anticipate future groundwater use and management challenges through planning, sustainable utilization, and effective protection of groundwater resources (Tuinhof et al., 2011; Gorelick and Zheng, 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 years, there has been a substantial decline in hydrometeorological data collection and management in Africa (Houghton-Carr and Fry, 2006; Robins et al., 2006). Decades ago, Africa had a relatively dense network of stations to measure rainfall, temperature and other weather data, but some weather centres have aged badly because of reductions in budgets for field maintenance and inspection, and many of these stations are no longer operating (Giles, 2005). The current density of hydrometeorological stations in Africa is eight times lower than the 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 management, and current efforts have mainly focused on rainfall and river flow data collection. As a result, most African countries lack groundwater-monitoring stations and this limits the understanding of the response of groundwater to human and natural conditions (Gaye and Tindimugaya, 2012).

Over the last decade, significant advances in the remote sensing techniques have led to a more complete overview of the water cycle at the global scale. Launched in March 2002, the Gravity Recovery and Climate Experiment (GRACE) is the first satellite mission able to provide global observations of terrestrial water storage changes (ΔTWS) (Richey et al., 2015; Chen et al., 2016). Given that the dynamics of groundwater are affected by inter-annual to multi-decadal climate 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 evolution of groundwater resources, as well as to provide pointers for the future.

To overcome GRACE's time frame limitation and the lack of adequate long-term piezometry data, this study used an approach to reconstruct past water storage variations in major aquifers across Africa through a climate-driven model using precipitation and actual evapotranspiration data from global datasets over the period of 1982 to 2011. Validation of the results is carried out by comparing the results of modeled total water storage changes (ΔTWS_{MODEL}) with GRACE-based total water storage changes (ΔTWS_{GRACE}) estimates from 2002 to 2013. The model and GRACE-based estimates are then compared to long-term piezometry measurements to show the extent to which total water storage changes covary with observed groundwater storage changes ($\Delta GWS_{OBSERVED}$). Using this approach also allows one to quantify teleconnections between total water and groundwater storage changes with global-scale climatic oscillations such as the El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Atlantic Multidecadal Oscillation (AMO).

Acronyms and abbreviations are given in the Appendix.

2. Background

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).

With regards to storage, a considerable proportion of Africa's groundwater resources is located in the large sedimentary basins in (semi)arid zones (e.g. North Africa, Sahel, and the Kalahari and Karoo basins in Southern Africa) and tropical zones (e.g. the Congo Basin in Central Africa) (MacDonald et al., 2012). These basins usually contain multi-layered aquifer systems with major alluvial formations forming shallow unconsolidated aquifers underlain by consolidated sedimentary rocks forming deeper aquifers. Even in semi-arid parts of Africa the shallow unconsolidated aquifers can be recharged in response to episodic storm events, climate oscillations, and land-use change (Taylor et al. 2009, 2013b). In the Sahara/Sahel aquifers, isotope and hydrochemical investigations have revealed that recharge mainly occurs by direct infiltration of rainwater or by river/surface water interaction as in the case of the Senegal and Niger Rivers (Diaw et al., 2012; Nazoumou et al., 2015; Abdou Babaye et al., 2018). Stable and radioactive isotopes contents in shallow aquifers confirm the presence of modern infiltration water (Lapworth et al., 2013; Zouari, 2015). Recharge rate over these areas are usually low and range from 0.1 to 5% of annual precipitation (Scanlon et al., 2006). The recharge mechanisms and dynamics of the deeper aquifers is still uncertain. Data from the Sahara/Sahel tend to exhibit piston-flow behavior (i.e. new water "pushing" old water downwards). Depleted stable isotopes 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).

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

INSERT TABLE 1 HERE

INSERT FIGURE 1 HERE

2.2. Climate variability modes in Africa

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

ENSO is considered as the most important pattern of natural interannual climate variability on Earth (Palmer and Anderson, 1994). It is a coupled ocean-atmospheric phenomenon that has interannual variability with irregular 2- to 7-year cycles between the warm (El Niño) and cold (La Niña) phases that has been occurring for at least the past 700 years (Li et al., 2013). El Niño is characterized by stronger than average sea surface temperatures in the central and eastern equatorial Pacific Ocean, reduced strength of the easterly trade winds in the Tropical Pacific, and an eastward shift in the region of intense tropical rainfall. La Niña is characterized by the opposite – cooler than average sea surface temperatures, stronger than normal easterly trade winds, and a westward shift in the region of intense tropical rainfall. Three very strong El Niño events have occurred since the early 1980s, i.e. 1982–1983, 1997–1998, and more recently 2015-2016. Although ENSO is centered in the tropics, the changes associated with El Niño and La Niña events affect climate around the world. ENSO's influence upon annual rainfall levels have been reported all across Africa, particularly in Southern Africa (Manatsa et al., 2011). Droughts occur most of the time during the warm phase of ENSO (Masih et al., 2014). On the other hand, the trend to more La Niña-like conditions since 2000 is a likely contributing factor driving the increase in Southern Africa rainfall (Maidment et al, 2015). As compared to the other African regions, the climate of Central Africa and its variability has been the subject of very few studies. The few existing studies suggest that there is not a significant relationship between ENSO and precipitation in Central Africa (Philippon et al., 2012; Taylor et al., 2013b). ENSO has also been linked to the devastating droughts of the 1970s and 1980s in the Sahel (e.g. Giannini et al., 2003). Drier (wetter) decades in the Sahel are usually correlated with El Niño (La Niña) events (e.g. Nicholson and Selato, 2000; Janicot et al., 2011). Several different ENSO indices have developed over time, but the Multivariate ENSO Index (MEI) is favored over other indices because it combines the significant features of all observed surface fields in the tropical Pacific. MEI monthly values were obtained from the NOAA Earth System Research Laboratory (NOAA, 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 low-pressure 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 pressure over the subtropical Atlantic. The negative phase reflects the opposite. The NAO exhibits considerable interseasonal, interannual and multidecadal variability with irregular 1- to 24-year cycles (Hurrell 1995, Chelliah and Bell 2005), but has a dominant quasiperiod oscillation of 3 to 6 years and a less significant 8 to 10 year mode (Hurrell et al. 2003). The NAO is among the known modes of natural variability influencing North Africa precipitation on a variety of time-scales, especially in winter and early spring. Drier (wetter) decades in North Africa largely correspond to positive (negative) NAO phase (Lopez-Moreno et al., 2011). Correlations are however particularly stronger for negative NAO phases (Donat et al., 2014). For example, the negative phase of the NAO from the mid-1950s to late 1970s indicates relatively wet conditions with a gradual shift towards drier conditions in the early 1970s. Recent years have also been considered wetter. NAO monthly values were obtained from the NOAA Earth System Research Laboratory database (NOAA, 2017).

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

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

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

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

3.2. A modelling approach to extend the GRACE timeframe

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

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

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

Integration of Eq. 1 gives:

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

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

$$\Delta\text{TWS}_{\text{MODEL}} = \int Pdt - \int Edt - \int Rdt \approx \text{detrend}\left(\int Pdt - \int Edt\right) \qquad \text{(Eq. 3)}$$

In absence of detailed field data on all these storage components it is difficult to isolate the change in groundwater storage (ΔGWS), but under certain circumstances – to be judged by the modeller– it is plausible that ΔGWS is nearly equal to ΔTWS_{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 (ΔTWS_{MODEL}).

3.3.Ground-based measurements

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

INSERT TABLE 2 HERE

INSERT FIGURE 2 HERE

3.4.Wavelet analysis

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

4. Results and discussion

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

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

INSERT FIGURE 3 HERE

INSERT FIGURE 4a HERE

INSERT FIGURE 4b HERE

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

INSERT FIGURE 5 HERE

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

INSERT FIGURE 6 HERE

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).

INSERT FIGURE 8 HERE

4.2. Groundwater storage variability and its association with climate teleconnections

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

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

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

INSERT FIGURE 9 HERE

INSERT FIGURE 10 HERE

WTC plots for the Stampriet Transboundary Aquifer System and the Karoo Sedimentary Aquifer in Southern Africa also reveal important correlation between groundwater storage and ENSO events with El Niño (La Niña) events usually leading to drier (wetter) conditions and decreasing (increasing) water levels (Figure 8). The dynamics of these aquifers are not similar and thus indicates that other climate modes might also be exerting an influence in Southern Africa. Previous studies present clear evidence of the importance of the Indian Ocean Dipole (IOD) 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 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.

INSERT FIGURE 11 HERE

5. Conclusions

A two-variables climate-driven model using precipitation and actual evapotranspiration data from global datasets was developed to reconstruct past total water storage changes in Africa from 1982 to 2011. Although the model has the important limitation of not considering human influences such as abstraction, land-use changes, and dam management, it offers robust pointers to assess the monthly dynamics of groundwater storage at very little computational cost as model-based total water storage changes ΔTWS_{MODEL} and observed groundwater storage changes $\Delta GWS_{OBSERVED}$ (representative of shallow groundwater fluctuations) are strongly correlated. GRACE-based ΔTWS_{GRACE} estimates are also highly correlated with model-based ΔTWS_{MODEL} and $\Delta GWS_{OBSERVED}$. As GRACE Follow-On (GRACE-FO) mission is scheduled to be launched in early 2018, ΔTWS_{GRACE} estimates will thus prove to be a well-founded tool to provide a general overview at basin scale of groundwater storage changes that are associated to 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.

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

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

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

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

Table 2 – Ground-based measurements in the studied aquifers

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

N/A : not applicable

FIGURE CAPTIONS:

Figure 1 – Location of the studied aquifers in Africa

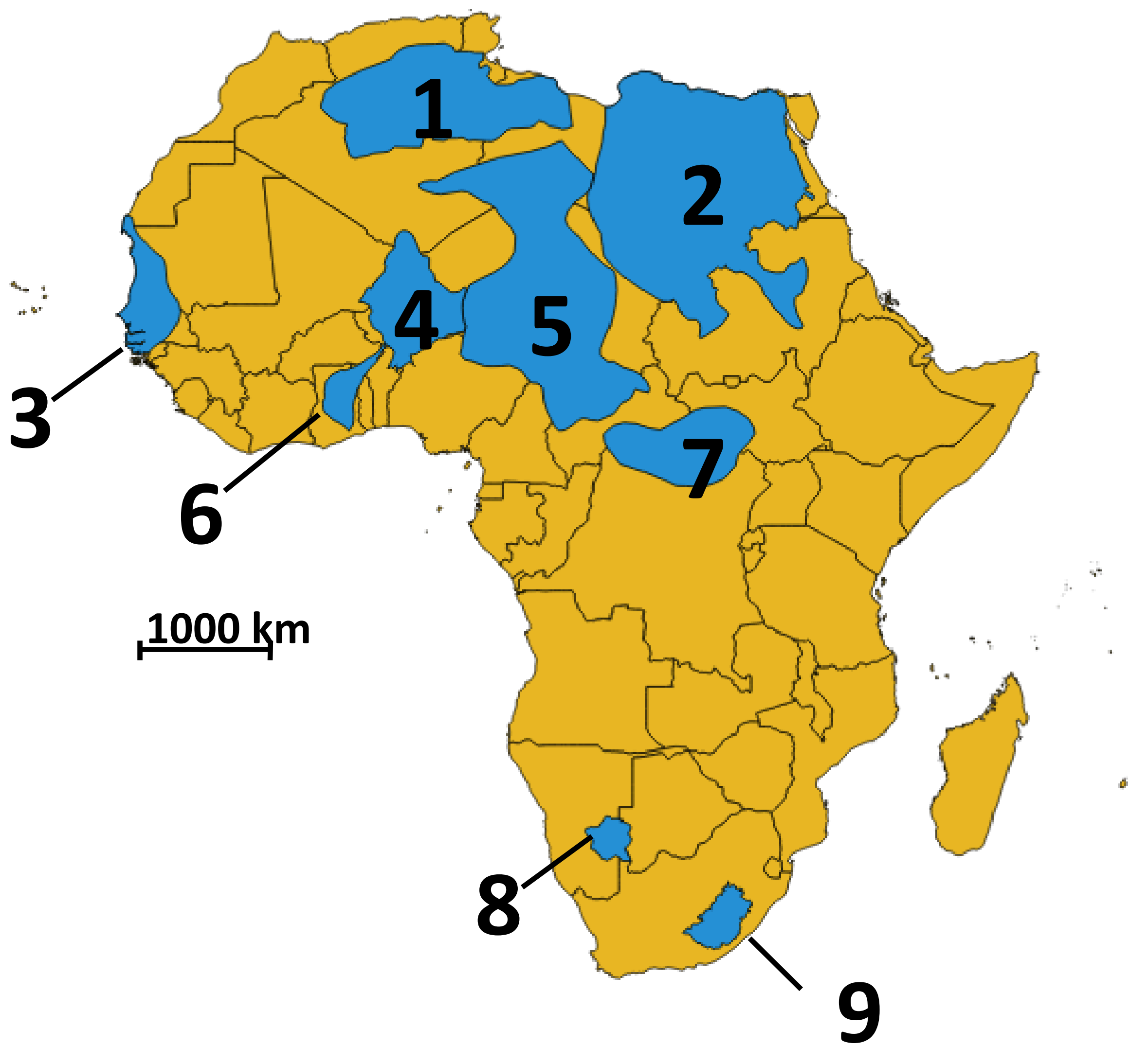


Figure 2 – Groundwater level fluctuation in the studied aquifers

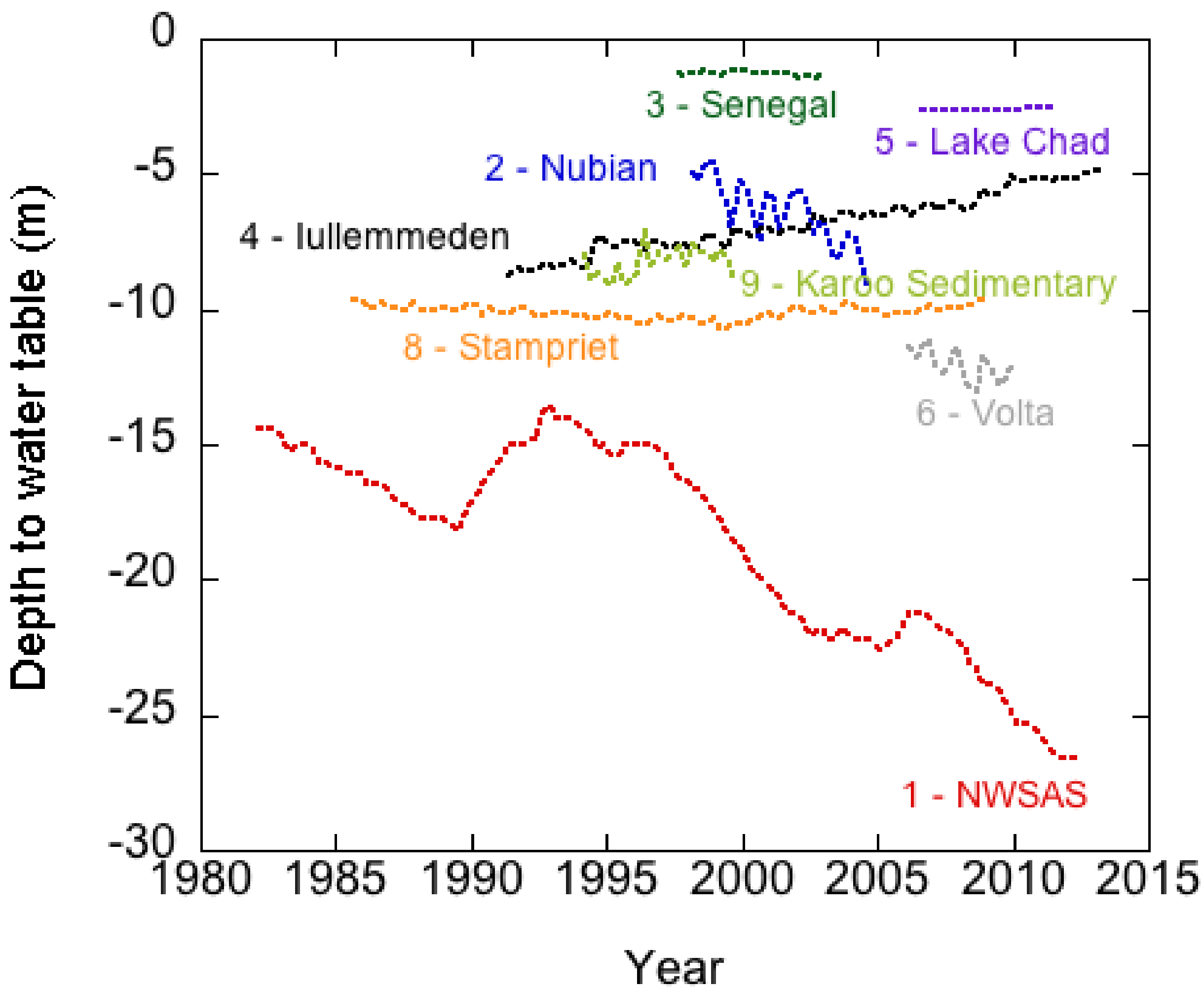


Figure 3 – Normalized observed groundwater $\Delta GWS_{OBSERVED}$ (red), GRACE-based ΔTWS_{GRACE} (blue) and model-based total water storage variability ΔTWS_{MODEL} (green) in the studied aquifers

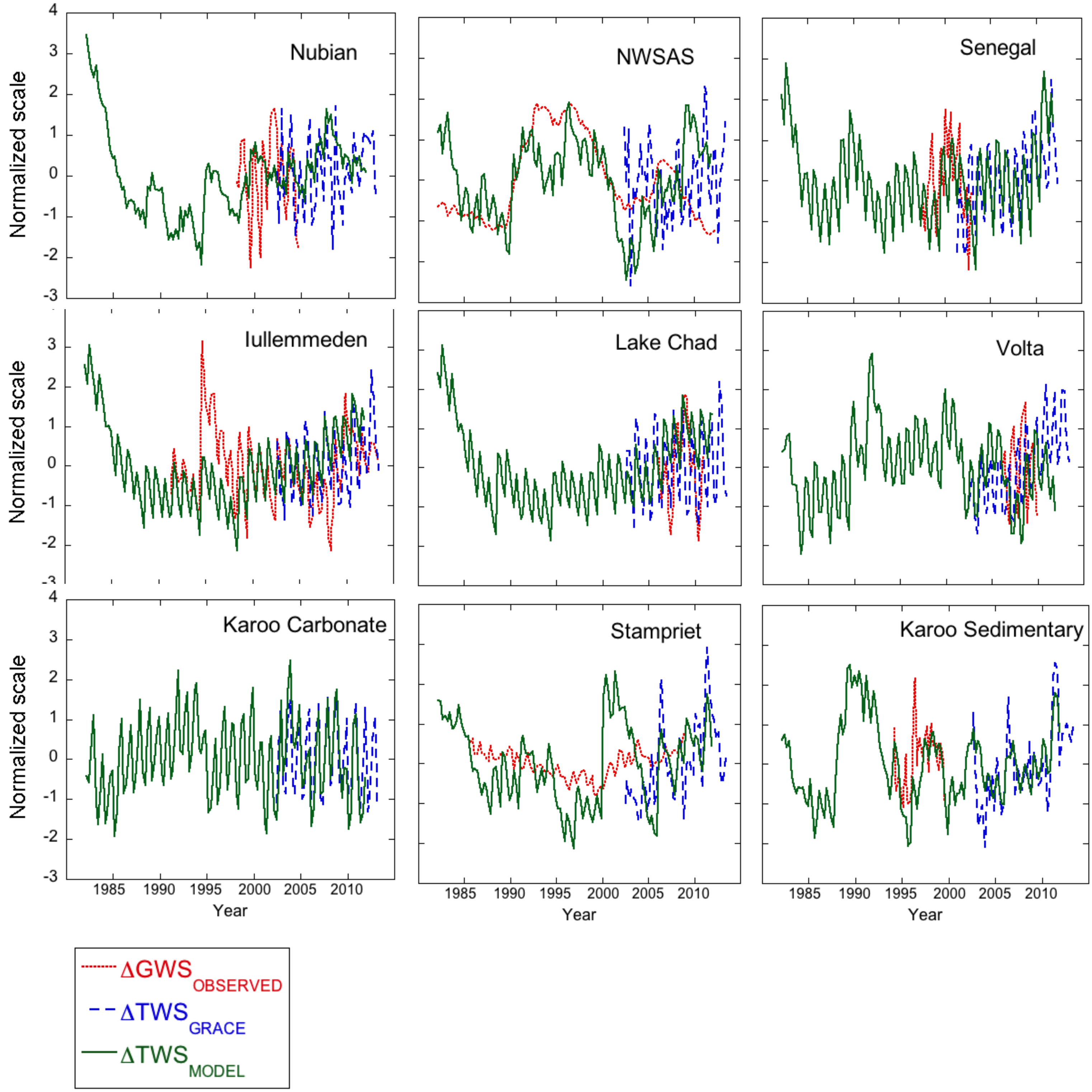
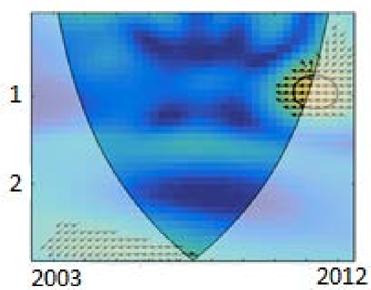
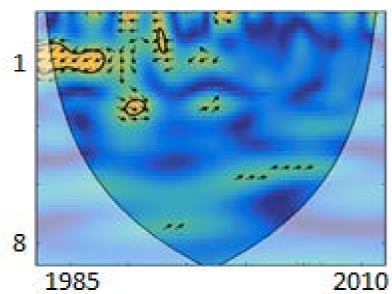
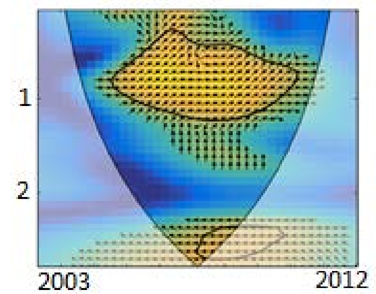
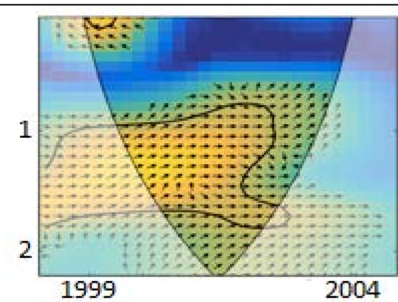
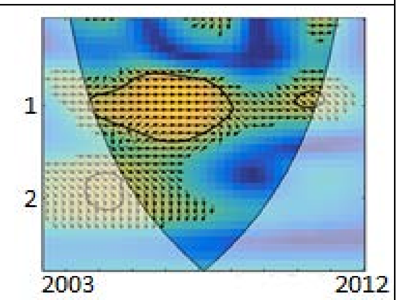
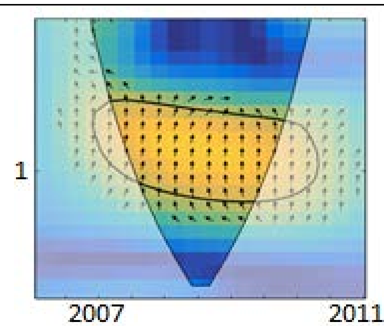
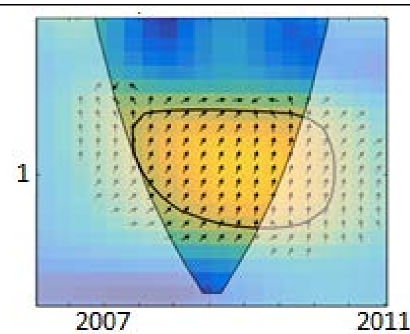
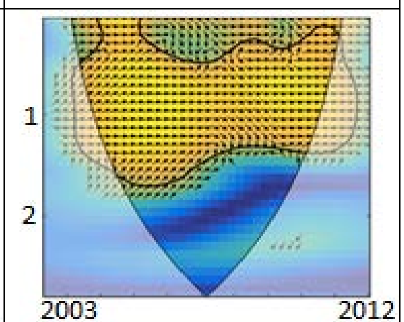
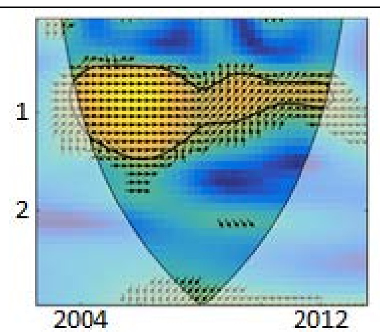
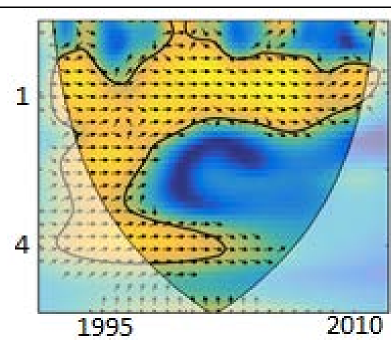
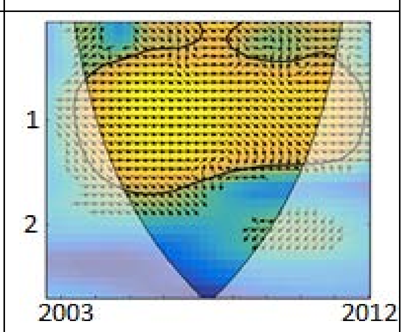
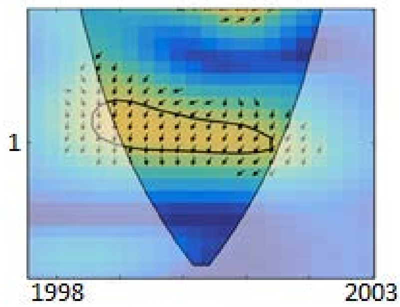
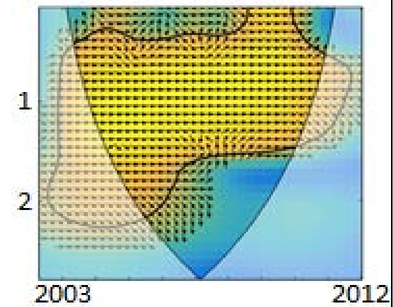
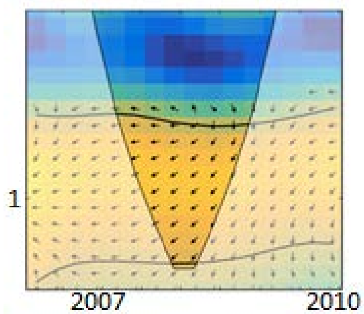
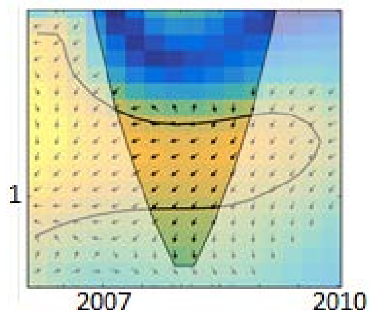
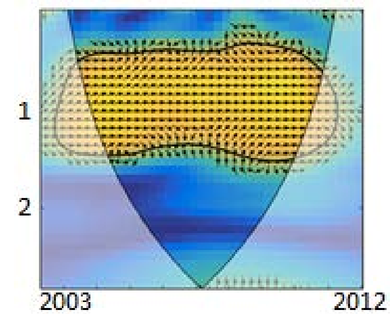
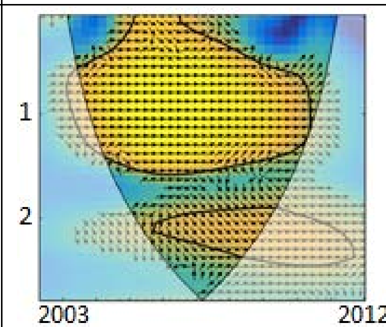
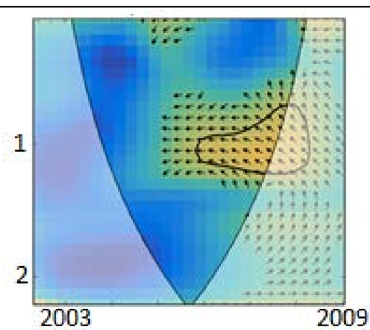
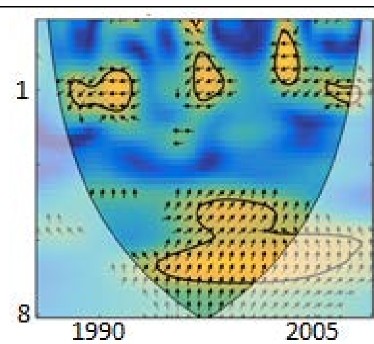
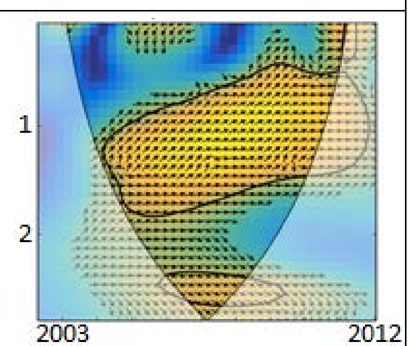


Figure 4 – Wavelet coherence (WTC) plots in the studied aquifers: **a** Northern Africa and Sahara-Sahel, and **b** Tropical/Equatorial Africa and Southern Africa
(Note: x-axis is date (year) and y-axis is period in years. Correlation coefficients vary from 0 (dark blue) to 1(light yellow))

a		**Groundwater level / GRACE**	**Groundwater level / Model**	**GRACE / Model**
1	North-Western Sahara Aquifer System			
2	Nubian Sandstone Aquifer System	N/A		
3	Lake Chad Basin			
4	Irhazer-Illuemeden Basin			

5	Senegalo-Mauretanian Basin	N/A		

b		**Groundwater level / GRACE**	**Groundwater level / Model**	**GRACE / Model**
6	Volta Basin			
7	Karoo Carbonate	N/A	N/A	
8	Stampriet Transboundary Aquifer System			

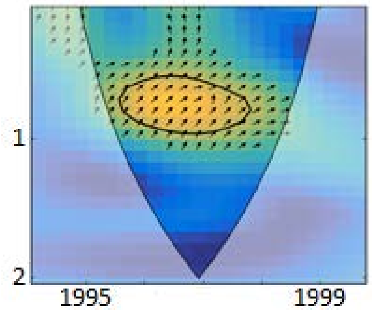
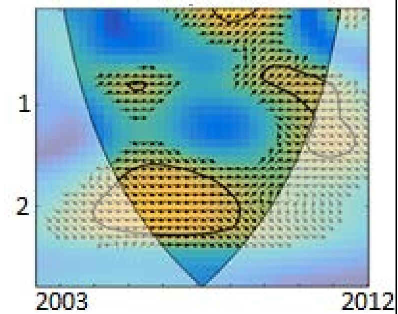
9	Karoo Sedimentary	N/A		

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)

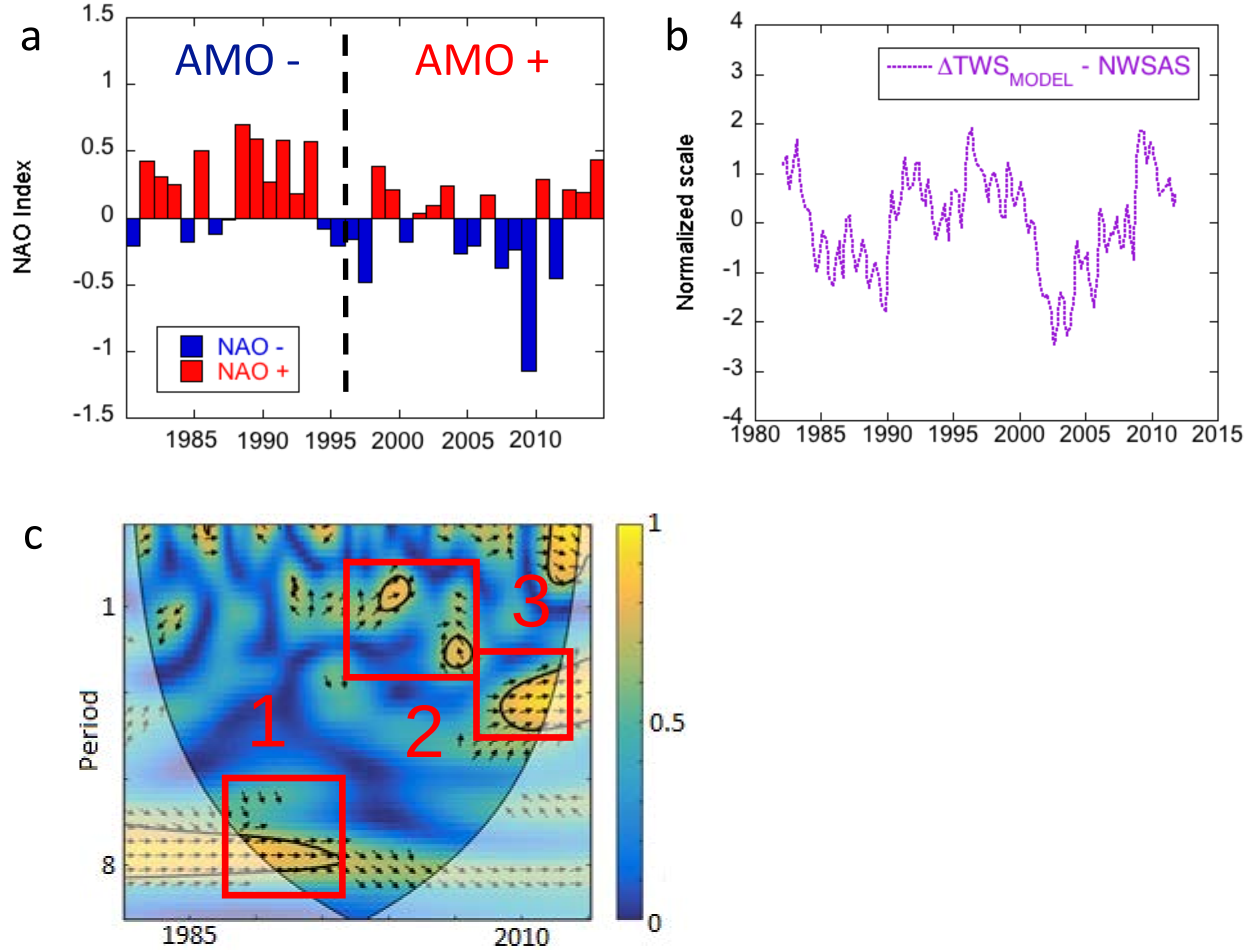


Figure 6 – Groundwater storage variability and its association with climate teleconnections in the Sahel (1982-2011): **a** Atlantic Multi-Decadal Oscillation (AMO) index and **b** simulated changes in total water storage (ΔTWS_{MODEL})

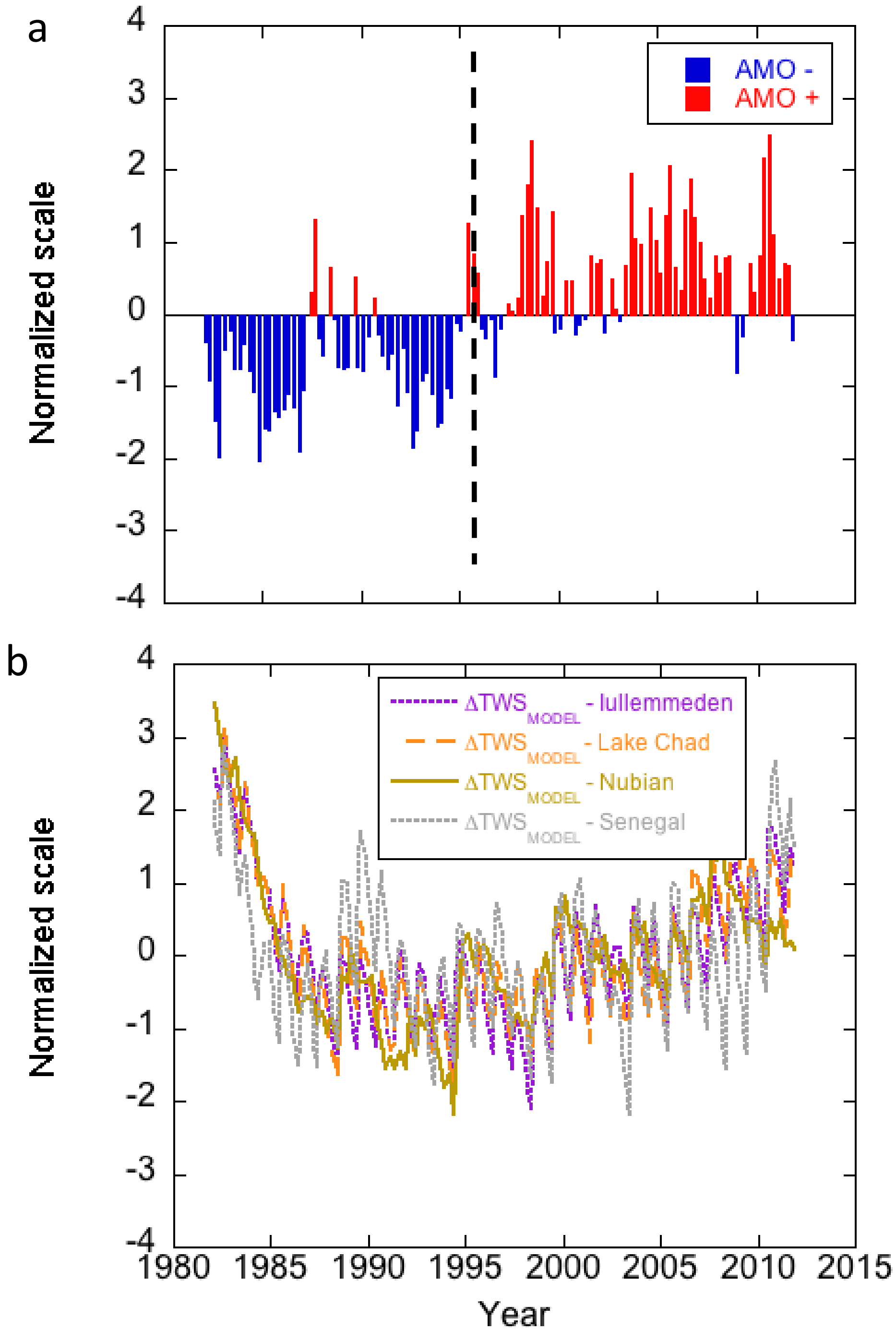


Figure 7 – Groundwater storage variability and its association with climate teleconnections in Equatorial Africa (1982-2011): **a** Atlantic Multi-Decadal Oscillation (AMO) index and **b** simulated changes in total water storage (ΔTWS_{MODEL})

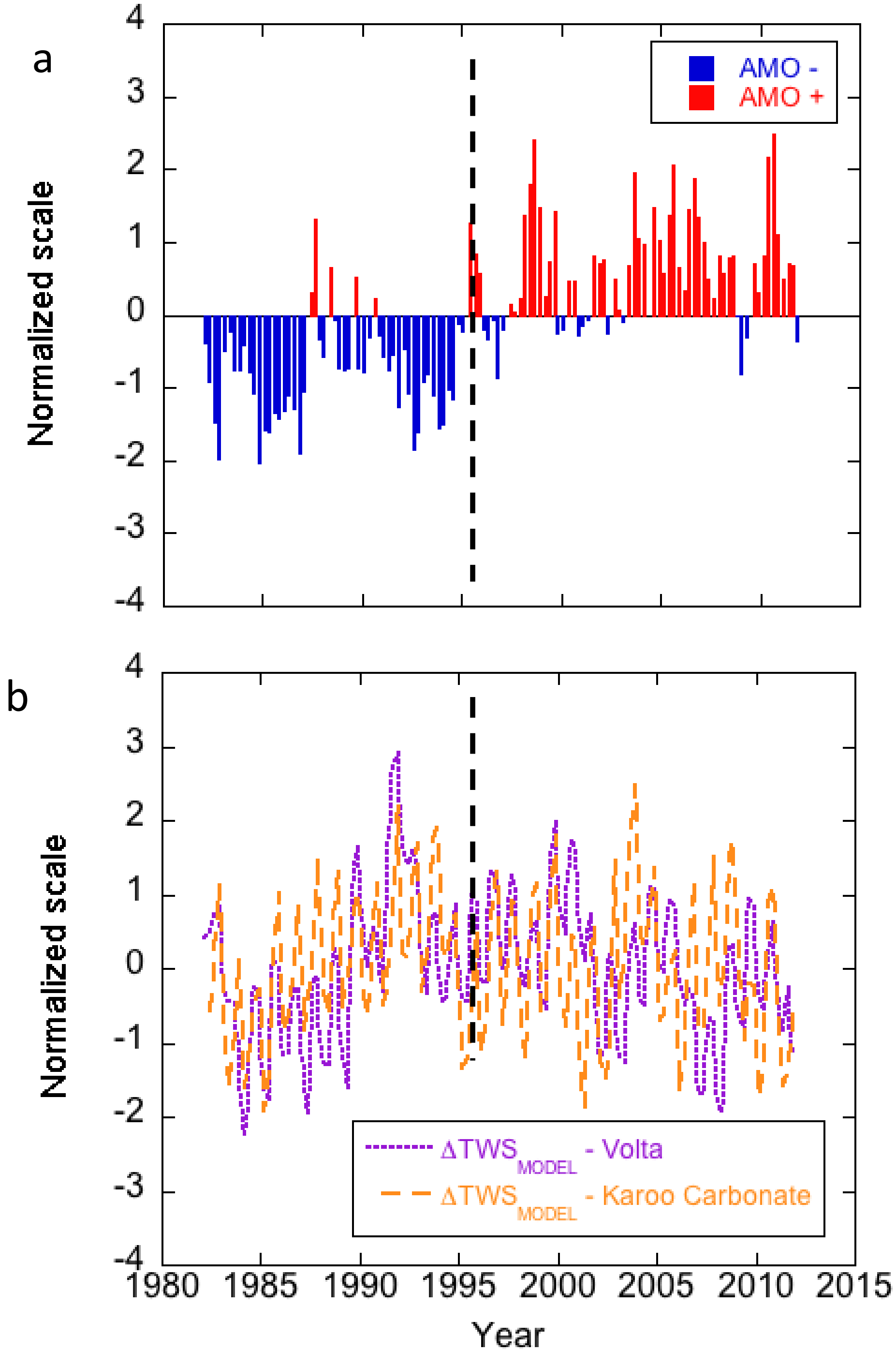
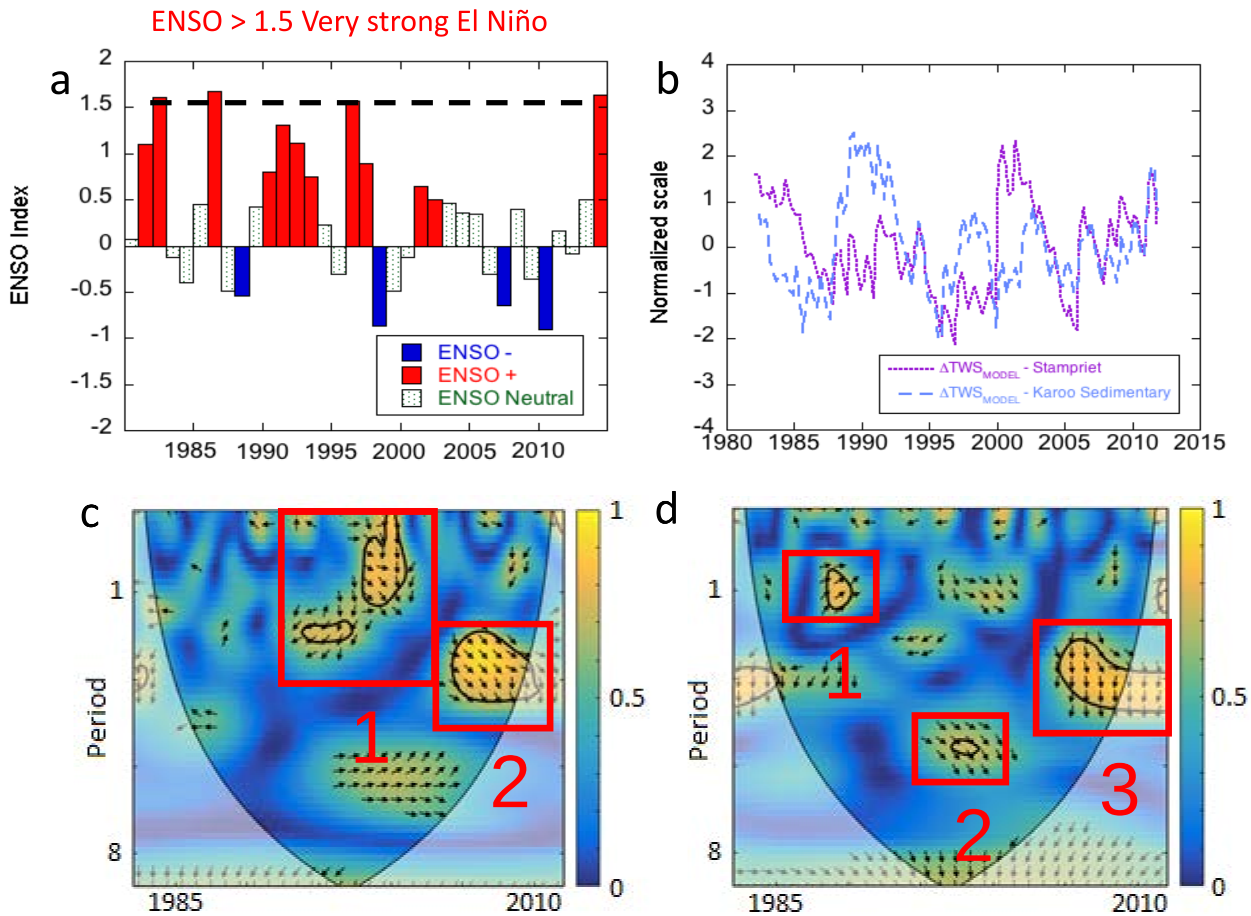


Figure 8 – Groundwater storage variability and its association with climate teleconnections in Southern Africa (1982-2011): **a** El Niño Southern Oscillation (ENSO) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL}-ENSO wavelet coherence plots for the **c** Karoo 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)



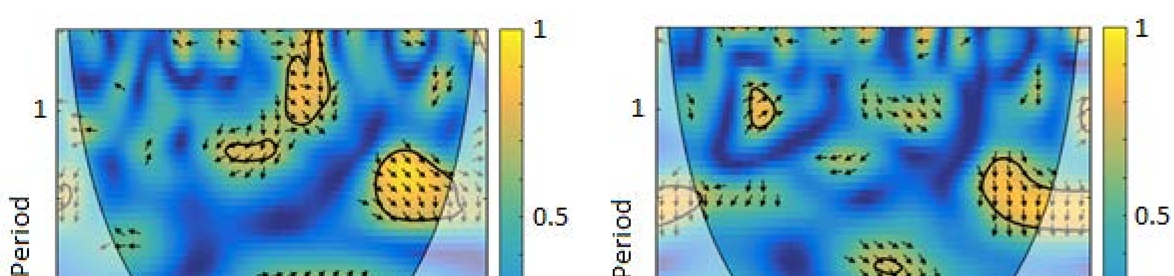


Figure 9 - Groundwater storage variability and its association with climate teleconnections in the Sahel (1982-2011): **a** El Niño Southern Oscillation (ENSO) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL}-ENSO wavelet coherence plots for the **c** Nubian Sandstone 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)

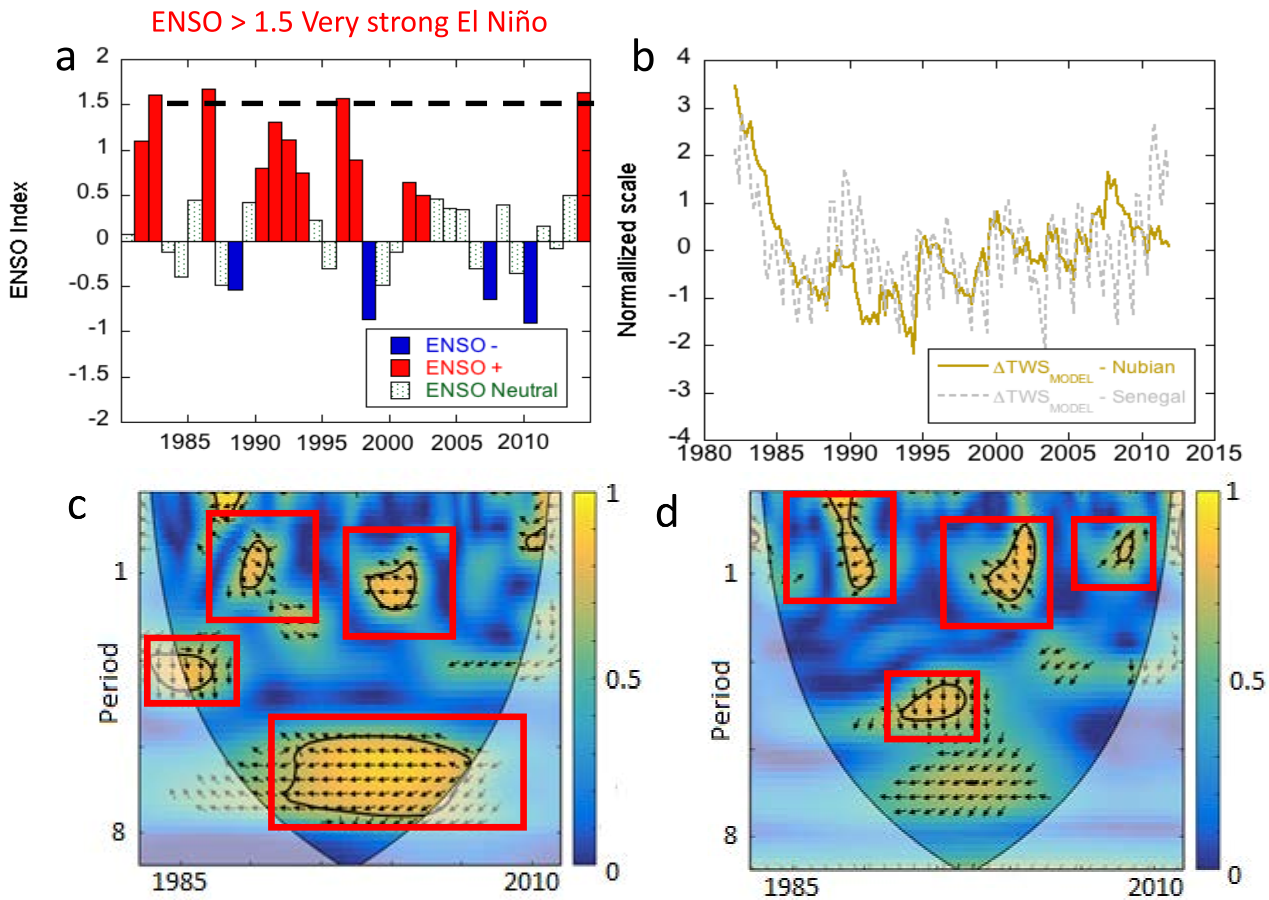


Figure 10 – Groundwater storage variability and its association with climate teleconnections in Equatorial Africa (1982-2011): **a** El Niño Southern Oscillation (ENSO) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL}-ENSO wavelet coherence plots for the **c** Volta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

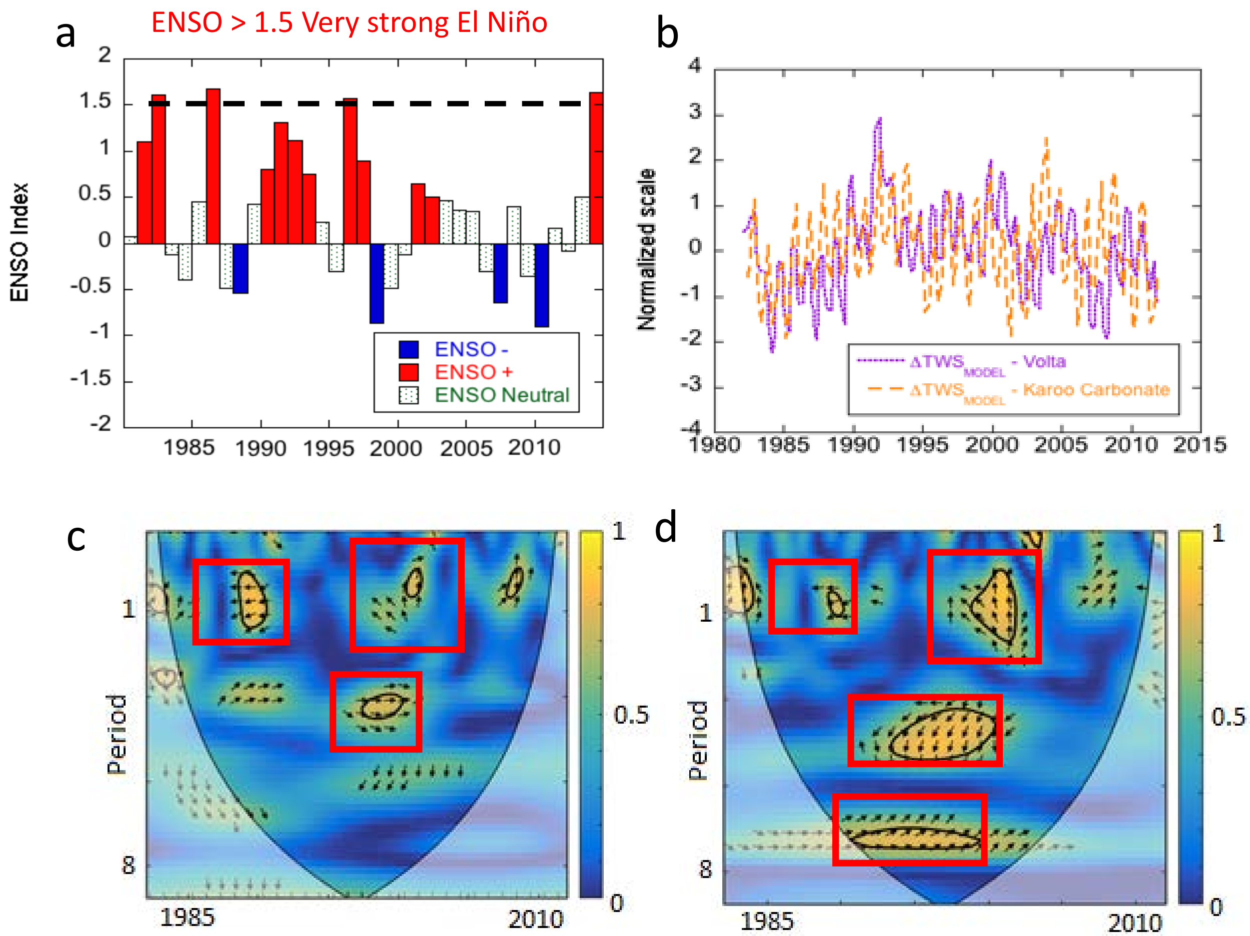


Figure 11 – Groundwater storage variability and its association with the Indian Ocean Dipole (IOD) index in Eastern Africa (1982-2011): **a** Indian Ocean Dipole (IOD) index, **b** simulated changes in total water storage (ΔTWS_{MODEL}); and ΔTWS_{MODEL}-IOD wavelet coherence plots for the **c** Nubian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