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Changes in hydro-meteorological conditions over tropical West Africa (1980–2015) and links to global climate

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ABSTRACT

The role of global sea surface temperature (SST) anomalies in modulating rainfall in the African region has been widely studied and is now less debated. However, their impacts and links to terrestrial water storage (TWS) in general, have not been studied. This study presents the pioneer results of canonical correlation analysis (CCA) of TWS derived from both global reanalysis data (1980–2015) and GRACE (Gravity Recovery and Climate Experiment) (2002–2014) with SST fields. The main issues discussed include, (i) oceanic hot spots that impact on TWS over tropical West Africa (TWA) based on CCA, (ii) long term changes in model and global reanalysis data (soil moisture, TWS, and groundwater) and the influence of climate variability on these hydrological indicators, and (iii) the hydrological characteristics of the Equatorial region of Africa (i.e., the Congo basin) based on GRACE-derived TWS, river discharge, and precipitation. Results of the CCA diagnostics show that El-Niño Southern Oscillation related equatorial Pacific SST fluctuations is a major index of climate variability identified in the main portion of the CCA procedure that indicates a significant association with long term TWS reanalysis data over TWA ($r = 0.50$, $\rho < 0.05$). Based on Mann-Kendall's statistics, the study found fairly large long term declines ($\rho < 0.05$) in TWS and soil moisture (1982 − 2015), mostly over the Congo basin, which coincided with warming of the land surface and the surrounding oceans. Meanwhile, some parts of the Sahel show significant wetting (rainfall, soil moisture, groundwater, and TWS) trends during the same period (1982–2015) and aligns with the ongoing narratives of rainfall recovery in the region. Results of singular spectral analysis and regression confirm that multi-annual changes in the Congo River discharge explained a considerable proportion of variability in GRACE-hydrological signal over the Congo basin ($r = 0.86$ and $R^2 = 0.70$, $\rho < 0.05$). Finally, leading orthogonal modes of MERRA and GRACE-TWS over TWA show significant association with global SST anomalies.

1. Introduction

Global interest in climate change is growing because of its anticipated impacts on agriculture, water security, and economic growth. As projected, impacts of climate change is expected to have direct and profound negative effects on freshwater availability (see, e.g., Tall et al., 2016; Prudhomme et al., 2014; Schewe et al., 2013). As a result, the focus on changes in hydro-meteorological conditions and water resources is receiving increasing attention (e.g., Andam-Akorful et al., 2017; Ndehedehe et al., 2016a; Hall et al., 2014; Shiferaw et al., 2014; Zhang et al., 2009; Conway et al., 2009; Descroix et al., 2009; Bekoe and Logah, 2013), especially with the perceived risk and vulnerability of future losses and socio-economic problems (e.g., migration and famine) resulting from the acceleration of the water cycle.

Extreme hydro-meteorological conditions and strong hydrological variability are unpredictable outcomes of changes in global climate that impacts on socio-economic systems of the world. In Thailand, for example, about 59 billion dollars was lost to the 2011 flood while economic growth was down by 38% due to hydrological variability in Ethiopia (see, Hall et al., 2014). Whereas the productive seasons of the year are restricted in monsoonal and tropical climates of the world due to strong seasonal and inter-annual rainfall variability (see, Hall et al., 2014), the preponderance of evidence from considerable case studies in the African sub-region (see, e.g., Ndehedehe et al., 2016b; Nicholson, 2013; Mohino et al., 2011a; Bader and Latif, 2011; Losada et al., 2010; Giannini et al., 2008; Todd and Washington, 2004; Nicholson et al., 2000) confirm that atmospheric circulation features, warming of the tropical oceans, mesoscale convective systems, and climate

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teleconnections, amongst others have large impacts on meteorological processes and induce extreme climatic conditions. Such impacts, teeming up with other low-frequency variability that are connected to slow oceanic and climate signals from global sea surface temperature (SST) anomaly (e.g., Diaz et al., 2001; Enfield and Mestas-Nuñez, 1999; Latif and Barnett, 1996), may have profound influence on hydrological changes and water resources.

Studies of changes in global climate and how they impact on meteorological and hydrological processes, are without doubt, emerging as active research. So far, our understanding of global climate has improved due to significant progress and advances made in global and regional climate models (i.e., GCMs and RCMs) (see, e.g., Tall et al., 2016; Erfanian et al., 2016; Prudhomme et al., 2014; Dimri et al., 2013; Schewe et al., 2013; Mishra et al., 2012; Li et al., 2004; Lebel et al., 2000). However, in regions where strong hydrological variability have been linked to multiple environmental phenomena such as large scale ocean-atmosphere phenomenon (e.g., Joly and Voldoire, 2010; Redelsperger and Lebel, 2009), land use changes (e.g., Favreau et al., 2009; Descroix et al., 2009), and other human interventions (e.g., surface water schemes) (e.g., Ngom et al., 2016; Ndehedehe et al., 2017a; Ahmed et al., 2014), the skills of climate and hydrological models may be restricted. Primarily, this maybe due to a number of factors that include, e.g., model dependence on computational estimates, model physics, choice of parameterisations, bias, conceptual model and parameter uncertainties (e.g., Oettli et al., 2011; Schuol and Abbaspour, 2006; Koster et al., 2004; Lebel et al., 2000). Despite their potential useful applications in optimization of water allocation schemes, early warning systems, and estimation of water availability (e.g., Thiemig et al., 2013), the restrictions of outputs from hydrological models, may affect meaningful management decisions related to water resources.

The failure of GCMs to produce a realistic climatology in West Africa, for example, can be damaging to hydrological applications (see, Lebel et al., 2000). All of the aforementioned issues represent significant setbacks that have contributed to the poor understanding of hydrological variability (e.g.,Hall et al., 2014), especially in Africa, a region characterised by strong inter-annual variability. The lack of sufficient in-situ and direct observations of land surface data (e.g., Alsdorf and Lettenmaier, 2003; Lettenmaier, 2005; Robock et al., 2000) generally affects regional configurations and adequate initialization of models (e.g., Jenkins et al., 2002) for the purposes of hydrological studies. This problem can only be more intense in non-industrialised regions such as tropical West Africa (TWA) (Fig. 1), where in-situ observations are either considerably sparse or unavailable (see, Conway et al., 2009) due to lack of robust investments in gauge measurements. Hence, more research using auxiliary data synthesized by forcing global land surface models with historical meteorological data (e.g.,Paolino et al., 2012; Sheffield and Wood, 2008), are required to further assess the representation of the land surface and atmospheric states in global reanalysis models.

TWA is indeed a strong climatic hot spot that play key roles in global climate. For instance, the Congo basin's rainfall climatology dominates global tropical rainfall during transition seasons (see, Washington et al., 2013). The long term decline in vegetation greenness in the Central African rainforests, the second-largest on Earth (Zhou et al., 2014), are indications that global biodiversity are under significant threat due to climatic disturbance. Sheffield and Wood (2008) found large increase in drought extent over West Africa compared to other global terrestrial areas. Furthermore, observed trends in the magnitude and frequency of flood events in the Sahel and Sudano regions (Nka et al., 2015), strong water deficit anomalies in West and Central Africa during the 2005–2007 period (see, Ndehedehe et al., 2016a; Asefi-Najafabady and Saatchi, 2013), and the recent long term drying of Central African Republic (e.g., Hua et al., 2016), are without doubt coherent impacts of climate variability and indicators of climate change in the region. Although it is now less debated that the global SST anomalies regulate rainfall in TWA (see, e.g., Odekunle and Eludoyin, 2008; Nicholson and Webster, 2007; Fontaine and Bigot, 1993; Semazzi et al., 1988; Nicholson, 2013, and the references therein), their impacts on and links to TWS and water fluxes (e.g., river discharge), in general, have not been studied. As with rainfall, the annual amplitudes and leading modes of land water storage (terrestrial water storage-TWS) and river discharge in TWA are presumably expected to be influenced by ENSO-related Pacific SST fluctuations and other triggers of ENSO, for example, SST anomalies of the north tropical Atlantic (see, e.g., Ham et al., 2013). Identifying the association between TWS and SST therefore requires consideration, and is significant to understanding global aspects of ENSO effects, for example, on regional hydrology.

As opposed to all of these aforementioned studies and those highlighted earlier, this study presents the pioneer results of canonical correlation analysis (CCA, e.g., Barnett and Preisendorfer, 1987; Graham et al., 1987; Glahn, 1968) of TWS derived from both reanalysis data and GRACE (Gravity Recovery and Climate Experiment) with global SST fields over TWA. The novel and underlying issues discussed include, (i) the linking of homogenous regions of TWS amplitudes to specific zones of global SSTs based on CCA, (ii) analysing the long term changes in water fluxes and state variables (rainfall, river discharge, soil moisture, TWS, and groundwater), and (iii) examining the hydrological properties of the Equatorial region of Africa (i.e., the Congo basin), which is prominently under-represented in hydrological research compared to other key global basins (see, Alsdorf et al., 2016). Since the global climate is also affected by tropospherically connected ENSO signals in other global oceans (see, e.g., Enfield and Mestas-Nuñez, 1999; Latif and Barnett, 1996), the link between long term changes in land water storage of the region and SST anomalies of the Pacific, Indian, and Atlantic Oceans requires reckoning. This is essential to (i) enhance the skills of hydrological models, (ii) close the gap of poorly understood complex regional hydrology and water fluxes, and (iii) examine the potential indices of climate variability that are associated with hydrological changes in TWA.

The three main objectives of this study are (i) to examine long term trends in water fluxes (1980–2015) and the influence of climate variability on long term changes in these water fluxes over TWA, (ii) to examine oceanic hot spots that impacts on TWS over TWA based on CCA, and (iii) to assess the hydrological characteristics of the Congo basin based on GRACE observations, river discharge, and precipitation.

2. Data

The data used in this study have been summarised in Table 1.

2.1. Terrestrial water storage (TWS)

(1) Modern-Era Retrospective Analysis for Research and Applications (MERRA)
National Aeronautic and Space Administration (NASA) global high-resolution MERRA reanalysis data (see, Rienecker et al., 2011) was used to analyse the long term TWS and soil moisture trends. The data is a state-of-the-art reanalysis that provides atmospheric fields, water fluxes, and global estimates of soil moisture (e.g., Rienecker et al., 2011; Reichle et al., 2011). Also, it has been improved significantly compared to previous reanalysis data sets (Rienecker et al., 2011). MERRA outputs have been used in the study of atmospheric circulations, agricultural drought assessment, and climate teleconnections in the African continent (e.g., Wu et al., 2013; Agutu et al., 2017; Ndehedehe et al., 2017b) and has been recommended for land surface hydrological studies (see, Reichle et al., 2011). The land TWS data component of MERRA used in this study, covers the period of 1980–2015 and is available for download through NASA's website (http://disc.sci.gsfc.nasa.gov/mdisc/). The MERRA-TWS (which are in $kg\,m^{-2}$ similar to millimeters —