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Understanding changes in terrestrial water storage over West Africa between 2002 and 2014

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ABSTRACT

With the vast water resources of West Africa coming under threat due to the impacts of climate variability and human influence, the need to understand its terrestrial water storage (TWS) changes becomes very important. Due to the lack of consistent in-situ hydrological data to assist in the monitoring of changes in TWS, this study takes advantage of the Gravity Recovery and Climate Experiment (GRACE) monthly gravity fields to provide estimates of vertically integrated changes in TWS over the period 2002–2014, in addition to satellite altimetry data for the period 1993–2014. In order to understand TWS variability over West Africa, Principal Component Analysis (PCA), a second order statistical technique, and Multiple Linear Regression Analysis (MLRA) are employed. Results show that dominant patterns of GRACE-derived TWS changes are observed mostly in the West Sahel, Guinea Coast, and Middle Belt regions of West Africa. This is probably caused by high precipitation rates at seasonal and inter-annual time scales induced by ocean circulations, altitude and physiographic features. While the linear trend for the spatially averaged GRACE-derived TWS changes over West Africa for the study period shows an increase of 6.85 ± 1.67 mm/yr, the PCA result indicates a significant increase of 20.2 ± 5.78 mm/yr in Guinea, a region with large inter-annual variability in seasonal rainfall, heavy river discharge, and huge groundwater potentials. The increase in GRACE-derived TWS during this period in Guinea, though inconsistent with the lack of a significant positive linear trend in TRMM based precipitation, is attributed to a large water surplus from prolonged wet seasons and lower evapotranspiration rates, leading to an increase in storage and inundated areas over the Guinea region. This increase in storage, which is also the aftermath of cumulative increase in the volume of water not involved in surface runoff, forms the huge freshwater availability in this region. However, the relatively low maximum water levels of Kainji reservoir in recent times (i.e., 2004/2005, 2007/2008, and 2011/2012) as observed in the satellite altimetry-derived water levels might predispose the Kainji dam to changes that probably may have a negative impact on the socio-economic potentials of the region. GRACE-derived TWS is not well correlated with TRMM-based precipitation in some countries of West Africa and apparently indicates a lag of two months over much of the region. On the other hand, the regression fit between GLDAS-derived TWS and GRACE-derived TWS shows R^2 of 0.85, indicating that trends and variability have been well modeled.

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1. Introduction

With an estimated population of 300 million people whose livelihood depends on rain-fed agriculture [see, e.g., 1–3], West Africa is one of the regions in the world with highly variable and extreme climatic conditions (i.e., droughts and floods), which impacts directly on the hydrological cycle and the human population. Despite its vast water resources, which includes lakes, rivers, wetlands, and groundwater systems, West Africa has a history of vulnerability to the impacts of climate change, which threatens these water resources and agriculture [e.g., 4,2,5–7].

More often than not, the region is subjected to food insecurity, famine, health issues, and social instability due to water related problems induced by the frequency and persistence of extreme

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hydrological/hydro-climatological conditions (e.g., droughts and floods) [see, e.g., 5,8–10]. Therefore, understanding the spatio-temporal variability of changes in terrestrial water storage (TWS) (i.e., the total of surface waters, soil moisture, canopy storage, and groundwater) in this region can support sustainable decisions and effective management of water resources. In addition, it can also provide information on the hydrological footprints, which probably can help reveal the impacts of climate variability on the region's TWS.

Furthermore, in West Africa, changes in any component of the TWS do have socio-economic and environmental implications [e.g., 11]. For example, as described in Moore and Williams [12] in a recent study in Africa, the surface waters are needed to maintain fisheries, which are a principal contributor to the food basket of the region. Consequently, changes to any component of these surface waters (i.e., lakes and rivers) or groundwater resources might jeopardize the livelihood and the economic viability of the region. Apparently, for a region such as West Africa that depends heavily on rain-fed agriculture; reduced rainfall and freshwater availability may lead to crop failure, and low agricultural productivity [13,10]. This ultimately will affect agricultural development and the economy of the region. Besides the reduced freshwater availability occasioned by changes in rainfall patterns of the region [14], the increasing irrigation development [13], ecosystem functioning and other various forms of anthropogenic influence puts water resources at risk [e.g., 4], hence the need to examine the changes in TWS and its variability over West Africa, which in the long term can support effective allocation, governance, and management.

Changes in TWS, be they groundwater, soil moisture, canopy storage, surface waters (i.e., lakes, wetlands, and rivers) remain one of the most critical components of the hydrological cycle. However, estimating these changes in TWS over West Africa remains a major challenge due to few in-situ monitoring stations, lack of large scale hydrological data, and unreliable field measurements amongst others. While Grippa et al. [11] specifically noted that the monitoring of water budget components in West Africa are hampered by scarcity of in-situ measurements, Anayah and Kaluarachchi [15] reported that the monitoring of groundwater in the upper east region of northern Ghana started in 2005 and continued until the end of 2008 (i.e., from 5 monitoring wells). Local measurements from dedicated networks such as the AMMA-CATCH[1] hydro-meteorological observing system have been used in validation studies [e.g., 17] and to characterize rainfall regime for the Gourma region located in Mali [e.g., 18]. However, hydrological studies over large spatially heterogeneous areas remain difficult as the AMMA-CATCH networks are highly insufficient and only available in few countries (i.e., Niger, Mali, and Benin). Besides the scarcity and the incomplete records of in-situ data in the sub-regions due to limited and degraded weather hydrological infrastructures precipitated by poor government funding, Nicholson et al. [19] reported that the acquisition of rainfall data despite its availability was largely hindered by political and economic instability, in addition to government policies. Due to these sparse in-situ meteorological and hydrological monitoring networks in West Africa, degraded hydrological infrastructures, data inaccessibility, and the gaps in routine measurements of relevant hydrological variables (e.g., river discharge, groundwater), our understanding of the spatio-temporal patterns of TWS changes is limited, hence the need for a large scale holistic assessment of water storage estimation. Due to the lack of in-situ hydrological data to assist in the accurate monitoring of TWS changes, indices such as effective drought index (EDI), standard precipitation index (SPI), and palmer drought severity index (PDSI) have been used as proxies for monitoring water availability and hydrological conditions [see, e.g., 20–23]. However, these indices do not account for the changes in the state of other water storage components (e.g., groundwater) [24], which is an important resource for livelihood. While it has been reported that these indices are associated with uncertainties [see, e.g., 25], the use of hydrological models has shown relatively good performance [26] on the one hand, and inconsistent results on the other hand [13]. However, land water storage output from models underestimate changes in water storage, and might be restricted due to limited data for evaluation and calibration purposes [9,27]. In order to circumvent this problem, previous studies have combined remote sensing data and outputs from models to improve the estimation of changes in TWS [e.g., 28,29].

Since March 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite mission under the auspices of National Aeronautic and Space Administration (NASA) in the United States and its German counterpart the Deutsches Zentrum für Luft-und Raumfahrt (DLR) has been collecting and archiving time variable monthly gravity fields [30]. These monthly gravity fields are provided as sets of spherical harmonic coefficients, which can be inverted to global and regional estimates of vertically integrated TWS at a spatial resolution of few hundred kilometers or more [31–33].

GRACE data has been used in the estimation of changes in TWS over West Africa in recent times. For instance, Grippa et al. [11] in a validation study, compared estimated TWS variations from different GRACE products with outputs from 9 land surface models operating within the framework of the African Monsoon Multidisciplinary Analysis Land Surface Inter-comparison Project (ALMIP). From the study, model outputs had a good agreement with GRACE-derived TWS changes. However, the analysis did not include the Western Sahel and some parts of Guinea coast, the region whose general rainfall pattern is highly influenced by ocean circulations and physiographic features. Ferreira et al. [34], 35] estimated mass changes and sink terms over the Volta basin in West Africa while Forootan et al. [14] proposed a prediction approach of TWS over West Africa for a duration of two years using a combination of past GRACE data, precipitation, and SST over the oceans. Still in West Africa, while Nahmani et al. [36] in a comparative study showed how the observed vertical deformation component from GPS data was fairly consistent with regional-scale estimates from GRACE satellite products and geophysical models, Hinderer et al. [37], had previously compared in-situ data from GPS with satellite observations such as GRACE in a project labeled Gravity and Hydrology in Africa. Furthermore, at continental and basin-wide scales, GRACE data have been used to investigate trends, and seasonal cycles of the various TWS components [see, e.g., 25,38–41]. For example, results of GRACE TWS solutions computed over Africa from 2003 to 2012 in Ramillien et al. [41] indicate a water loss from the North Saharan aquifers.

In order to improve our understanding of the land water storage over West Africa and to further extend the studies mentioned above, this study attempts to highlight the recent annual and seasonal variability of TWS changes for the period 2002–2014. Contrary to previous studies in the region, the approach here is to analyze the variability and the relationship between GRACE-derived TWS changes and rainfall patterns over West Africa using principal component analysis (PCA) [42,43] and multiple linear regression analysis (MLRA). The study looks into the inter-annual and seasonal variability of TWS changes, lake height variations of water reservoirs, and precipitation patterns. To evaluate GRACE-derived TWS changes over West Africa, total water storage content (TWSC) from the Global Land Data Assimilation System (GLDAS) [44] were also explored.

Therefore, this study explores hydrological fluxes such as precipitation and satellite altimetry data, alongside with TWS changes

[1] African Monsoon Multidisciplinary Analysis-Couplage Atmosphere Tropicale Cycle Hydrologique [16].

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