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Analysis of hydrological variability over the Volta river basin using in-situ data and satellite observations

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ABSTRACT

By combining satellite altimetry with Gravity Recovery and Climate Experiment derived terrestrial water storage-TWS (2002–2014), this study used a two-step procedure based on spherical harmonic synthesis and statistical decomposition to support the understanding of the Volta basin's natural hydrology and its freshwater systems. Results indicate that Lake Volta contributed 41.6% to the observed increase in TWS over the basin during the 2002–2014 period. The statistical decomposition of TWS over the basin (after removing the Lake's water storage) resulted in a statistically significant ($\alpha = 0.05$) loss of 59.5 ± 8.5 mm/yr of TWS in the lower Volta region of the basin between 2007 and 2011. This trend is attributed to a base flow recession resulting from the negative trends in precipitation around the lower Volta (2002–2014) and limited river flows of the Volta river system. While it also coincides with observed decline in net precipitation (−15 mm/yr), the long dry periods in the basin (2001–2007) also contributed to this storage depletion. The Lake Volta shows sensitivity to incoming flows of the Volta river system with a lag spanning between less than one and up to two years. In addition to this, a 4–5 year cycle in the clustering of dry and wet periods resulting from the impact of climate variability on the basin was noticed.

1. Introduction

Lake Volta, one of the highly esteemed projects from the period of Africa's decolonisation, is the largest man-made reservoir by surface area in the world, covering a total area of approximately 8500 km^2. This Lake, which was built in 1964, has an estimated capacity of 150 km^3 with an installed hydropower generation capacity of about 912 MW (e.g., Owusu et al., 2008; Gyau-Boakye, 2001). Besides being one of the most important surface water in West Africa, the Lake, which is formed by the Akosombo dam in Ghana, is a symbol of high socio-economic importance and progress in the region, and remains a major source of livelihood and hydro-power to approximately 20 million people whose livelihood depends on the Volta river basin (hereafter the Volta basin, Fig. 1).

The impact of extreme climatic conditions on the Lake is a timely topical research issue of public-policy interest due to its implications on the people and local economy. For instance, Ghana suffered power rationing during the hydrological drought years of 1983, 1998, and 2006, leading to shortfalls in the production of goods, unemployment, and reduced gross domestic product (see, e.g., Bekoe and Logah, 2013). Apparently, in the wake of global climate change, the impacts of extreme climate conditions on Lake Volta

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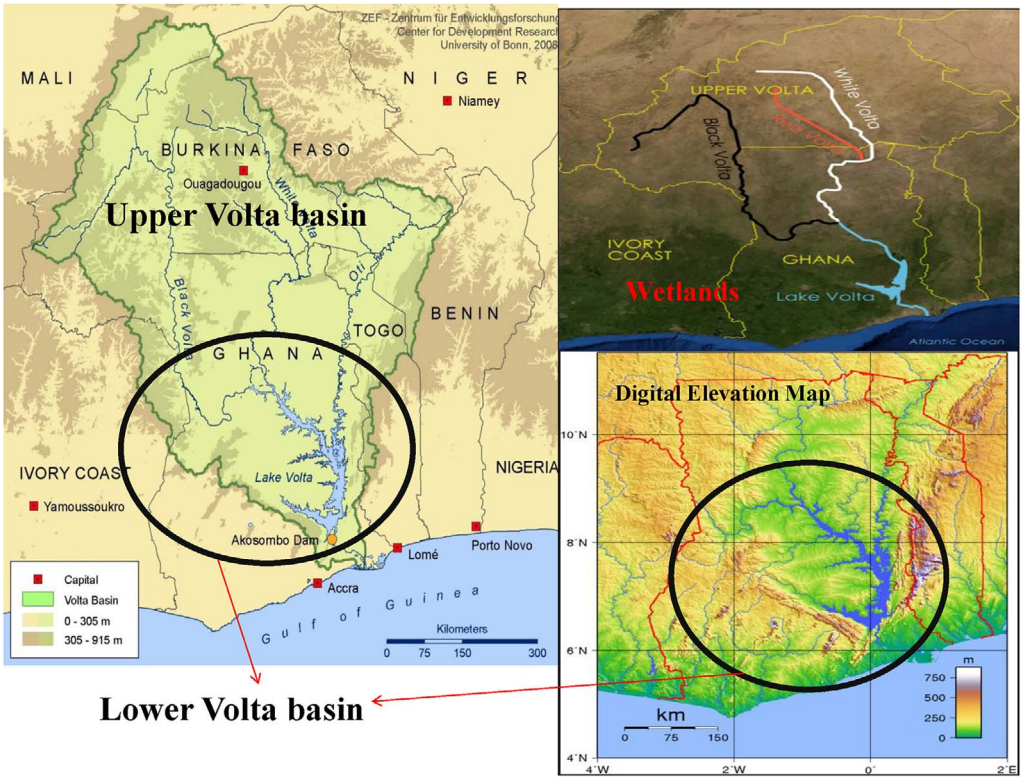

Fig. 1. Study area showing the Volta river basin. The riparian countries (Ghana, Togo, Benin, Burkina Faso, Mali, and Ivory Coast) of the basin are also indicated. The Lake Volta, the Volta river system (White Volta, Black Volta, and Oti rivers), and the location of the Akosombo dam have also been indicated. Original maps adapted from http://www.21stcentech.com/wp-content/uploads/2013/12/Volta-River-basin.jpg and https://en.wikipedia.org/wiki/Geography-of-Ghana.

could largely limit the generation of hydro-electric power in future, leading to untold hardship in the region. The low impoundment levels of Akosombo dam and the decline in Lake Volta's water level, owing to negative trends in rainfall (e.g., Owusu et al., 2008) are arguably indications of the region's vulnerability to the impacts of climate variability.

In the Volta basin, analysis of long term historical hydro-climatic conditions (1901–2002) have shown that large changes in water budget quantities (precipitation, river discharge, and evapotranspiration) have occurred (Oguntunde and Friesen, 2006). These changes, which impact on the local climate through feedback mechanisms and land atmosphere interactions, have the potentials of restricting the freshwater systems of the basin. As reported in earlier studies (e.g., Friesen et al., 2005; Andreini et al., 2000), the marked variability in rainfall and stream flow records in the pre and post construction periods of the Akosombo dam revealed the impact of damming on the basin. This inadvertently resulted in the non-linearity of hydrological processes, thereby complicating our understanding of the hydrological variability of the basin. One of such instance in the basin, is the observed decline in precipitation, which was inconsistent with observed increase in terrestrial water storage (TWS, i.e., the sum total of surface waters, soil moisture, and groundwater) derived from Gravity Recovery and Climate Experiment (GRACE, Tapley et al., 2004) during the 2003–2012 period (e.g., Ahmed et al., 2014; Moore and Williams, 2014). These observed trends in GRACE-derived TWS changes over the basin have been attributed to the impact of water ponding in the Akosombo dam (e.g., Ferreira and Asiah, 2015; Moore and Williams, 2014; Ahmed et al., 2014). Such impacts do have implications in water budget assessment and quantifying the impact of climate variability on the Volta basin's hydrology.

Although in some studies within the mainstream of water resources, droughts and GRACE-TWS have been reported in the Volta basin (e.g., Ndehedehe et al., 2016c; Bekoe and Logah, 2013; Ferreira et al., 2012; Owusu and Waylen, 2013; Kasei et al., 2010; Owusu et al., 2008; Oguntunde and Friesen, 2006; Friesen et al., 2005; Andreini et al., 2000, 2002; Giesen et al., 2001), the hydrological variability of the basin is largely unreported. In fact, the lack of clear perspectives regarding the impact of human activities on the hydrological changes of the basin have been partly and loosely attributed to increase in surface water storage in the reservoirs and decrease in soil moisture storage (e.g., Friesen et al., 2005). Although Giesen et al. (2010) argues that the causes of climate change in the basin remains unclear, however, the lack of in-situ data and existing data gaps in stream flow records of the region have particularly limited our understanding of the impacts of climate variability and the natural hydrology of the basin. The use of a non-physical based hydrological model to study the water balance of the basin as reported in Andreini et al. (2000) could be restricted as stream flow and rainfall could be affected by a number of factors, e.g., climate variability and human activities (e.g., water abstraction, land use change) amongst others (e.g., Bekoe and Logah, 2013; Owusu et al., 2008). Given the economic importance of the Lake Volta in hydropower generation for the southern catchment of the basin (Ghana) and the freshwater of the Volta river system for agricultural purposes in Burkina Faso, it is pertinent to understand the hydrological variability of the Volta

basin and the restrictions of climate variability on its water fluxes and freshwater systems (rivers, lakes, and TWS).

Consequently, the current study employs a multi-satellite approach to monitor and quantify recent inter-annual changes in GRACE-derived TWS over the Volta basin (also includes the Lake Volta). In Ndehedehe et al. (2016c), the potentials of multiple climate variables to assess hydrological droughts over the basin were considered, while GRACE-derived TWS variability over West Africa was analysed during the 2002–2014 period in Ndehedehe et al. (2016a). In contrast, here, we analyse for the first time the spatio-temporal variability of TWS over the Volta basin after removing the hydrological signal induced by Lake Volta water level changes (hereafter called Lake Volta induced TWS). In addition, the impact of climate variability on the basin's freshwater systems is considered. This is achieved using the Global Precipitation Climatology Centre based precipitation product (GPCC, Schneider et al., 2014), in-situ river discharge, evapotranspiration, and satellite altimetry data. Furthermore, use is made of a cumulant based statistical method, the independent component analysis (ICA, see, e.g., Common, 1994; Cardoso and Souloumiac, 1993; Cardoso, 1999) to support the localisation of hydrological signals that are masked by the dominant signals caused by the impact of large water projects such as the Akosombo dam.

Specifically, this study aims at (i) understanding the hydrological variability of the Volta basin, (ii) examining the contributions of Lake Volta to the overall trends in TWS over the Volta basin, and (iii) understanding the impact of climate variability on the freshwater systems of the Volta basin. As the Lake Volta provides hydropower and other multiple strings of ecosystem services to the region, this study is warranted essentially to support water resources planning and sustainability of the Lake and its catchment areas. Apart from investigating whether long term trends and changes in stream flow records and Lake levels in the basin are climate driven or human related (e.g., irrigation), the study employs a two-step procedure based on a weighted least squares formulation of global spherical harmonic analysis and statistical decomposition, to support the monitoring of spatio-temporal hydrological variability and trends resulting from natural climate variability in the basin.

The remainder of the study is structured as follows; in Section 2, a brief introduction to Lake Volta is provided while in Section 3, a description of the data is given. This is followed by the method used in Section 4 while the analysis and discussion of the results are provided in Section 5. The conclusion of the study is provided in Section 6.

2. Lake Volta

Lake Volta is located at the lower Volta basin, a low elevation area (cf. see digital elevation map, Fig. 1) that is naturally connected to the Volta river system (i.e., Oti, Black Volta, and White Volta rivers – Fig. 1) and other small freshwater tributaries. The aquifer system of the lower Volta seems to be rather confined with the Akosombo dam impounding surface water at the Lake. This natural connection of the Lake with the Volta river system leads to relatively strong inter-annual variability in TWS around the precinct of the lower Volta. During periods of extreme rainfall such as the 2007 La-Niña event (e.g., Paeth et al., 2012), the amplitudes of the Lake induced TWS become relatively strong due to heavy stream flows from the Volta river system creating a pseudo trend in TWS change over the basin that most times obscures other hydrological signals. Not only does the Lake induced TWS signal obscures other hydrological signals in the basin, it also complicates the natural hydrological setting of the lower Volta. For instance, in a recent study where the authors analysed hydrological drought over the basin (see, Ndehedehe et al., 2016c), it was noted that despite the significant fall in the amplitudes of annual rainfall (i.e., during the 2008–2013 period) and severe hydrological drought conditions in the Lake Volta area (i.e., 2010–2013 period), TWS over the basin increased significantly during these periods. While Ahmed et al. (2014) attributed the increasing trend in TWS over the basin (2003–2012) to water ponding by the Akosombo dam, Moore and Williams (2014) reported that the influence of major lakes such as the Lake Volta contributes significantly to the observed trend and seasonal changes in GRACE-derived TWS of the corresponding basin. Moreover, despite having a surface area (approximately 8500 km^2) that corresponds to 2% of the basin, Lake Volta, because of its strong change in water levels (see, Fig. 2), has the strongest hydrological signal, when compared to other Lakes in Africa (e.g., Lake Victoria with approximately 68,800 km^2 in surface area) with larger surface areas (see, Moore and Williams, 2014). Beyond that, the Lake Volta show strong fluctuations in trends (Fig. 2) of water level variations in recent times (see more details in Appendix A2). These impacts of the Lake's fluctuation in water levels during the 2002–2015 period on the hydrology of the basin is largely unreported. Investigating the impact of this Lake on the spatio-temporal changes of TWS in the Volta basin provides useful indications and broad scale assessments of the overall change

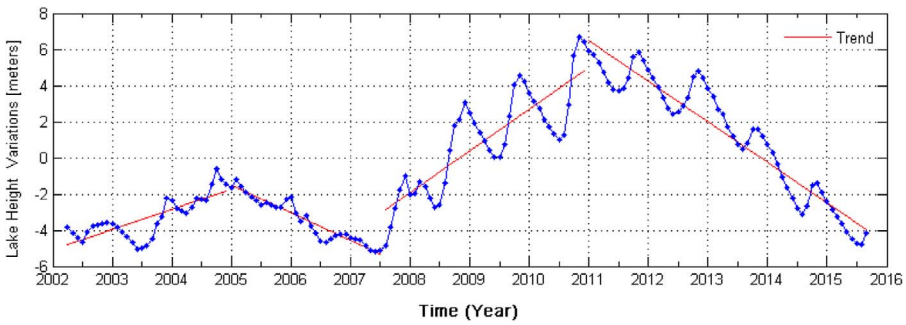

Fig. 2. Trends in lake height variations of Lake Volta after removing the temporal mean for the period (2002–2015). These trends and fluctuations in lake water level are discussed further in Appendix A2.

in hydro-climatic conditions. In addition to this, the opening of the spillways of the Akosombo dam, in order to allow excess water in the reservoir to flow down stream in November 2010 due to excess rainfall as reported by Owusu and Waylen (2013) is one of the isolated cases that may also impact on the changes in TWS over the basin, further complicating its hydrological variability. Consequently, the ICA technique has been employed to specifically support the localisation of obscured hydrological signals in the basin (i.e., after removing the lake induced TWS). The statistical decomposition of this residual water storage is shown and discussed in Section 5.2.

3. Data

3.1. Terrestrial water storage observed by Gravity Recovery and Climate Experiment (GRACE)

This study used GRACE (Tapley et al., 2004) Release-05 (RL05) spherical harmonic coefficients truncated at degree and order 60 from Center for Space Research (CSR), covering the period 2002–2014 (data files accessed at http://icgem.gfz-potsdam.de/ICGEM/shms/monthly/csr-rl05/). Continental water storage anomalies are one of the most important geophysical phenomena derived from these spherical harmonic coefficients and typically serves as the hydrological quantity of interest (see, e.g., Sneeuw et al., 2014; Wahr et al., 1998) in studies of terrestrial and ocean mass transport. Since GRACE satellites are insensitive to the degree 2 coefficients (i.e., C_{20}) of the gravity field due to orbit configuration (e.g., Seo et al., 2008; Schrama et al., 2007; Sneeuw et al., 2014), they were replaced by estimates from satellite laser ranging (Cheng et al., 2013). Also, since GRACE does not provide changes in degree 1 coefficients (i.e., C_{10}, C_{11}, and S_{11}), the degree 1 coefficients provided by Swenson et al. (2008) were used. Given that GRACE spherical harmonic coefficients are affected by noise in the higher degree coefficients (e.g., Belda et al., 2015; Landerer and Swenson, 2012; Swenson and Wahr, 2002), a regularization filter of Kusche (2007) was applied to reduce the effect of noise. This filter, which accommodates better the GRACE error structure when compared to the conventional isotropic Gaussian filter (see, e.g., Werth et al., 2009), reduces the north-south stripes in the GRACE monthly solutions. The filtered monthly solutions were then converted into equivalent water heights (EWH) on a $1^\circ \times 1^\circ$ grid using the approach of Wahr et al. (1998) as follows:

$$\Delta W(\psi, \lambda, t) = \frac{R\rho_{\text{ave}}}{3\varrho_w} \sum_{l=0}^{l_{\max}} \frac{2l+1}{1+k_l} \sum_{m=-l}^{l} P_{\text{lm}}(\psi, \lambda) \Delta Y_{\text{lm}}(t), \tag{1}$$

where ΔW is the EWH for each month in time (t), and ψ, λ are the geodetic latitudes and longitudes respectively. R is the mean radius of the Earth (i.e., 6378.137 km), ρ_{ave} is the average density of the Earth (5515 kg/m^3), ϱ_w is the average density of water (1000 kg/m^3), k_l is the load Love numbers of degree l, P_{lm} are the normalized associated Legendre function of degree l and order m with $l_{max} = 60$ and ΔY_{lm} are the normalized complex spherical harmonic coefficients of temporal anomalies of the geoid after subtracting the long term mean. The regularisation filter leads to leakage and attenuation of the signal's amplitude (e.g., Wouters and Schrama, 2007; Baur et al., 2009), hence a scaling factor was computed following Landerer and Swenson (2012) in order to account for the geophysical signal loss, which occurred during the pre-processing of GRACE data. Specifically, the scale factor was empirically derived using GLDAS-derived total water storage content (see more details in Section 3.5). Accounting for the leakage effect in GRACE observations has become necessary as the signal attenuation can contribute to significant errors in regional water balance studies (see Landerer and Swenson, 2012). Since we are also interested in average TWS values (i.e., ΔW) over the basin, the estimated EWH (hereafter called TWS), were averaged over the basin using area weighted averaging (see, e.g., Sneeuw et al., 2014):

$$\Delta W(\chi; t) = \sum\nolimits_{l=1}^{n} \Delta W(\psi_i, \lambda_i, t) \frac{A_i}{A_\chi}, \tag{2}$$

where χ is the basin index, n is the number of grid points in the basin, A_i is the area of the grid cell i in χ and A_χ is the total area of χ.

3.2. Satellite altimetry

Observed lake height variations computed from TOPEX/POSEIDON (T/P), Jason-1 and Jason-2/OSTM altimetry provided by the United States Department of Agriculture (USDA) were used in this study. The use of altimetry-based measurements for a data deficient region is beneficial since they are continuous and potentially available few days after measurement (Coe and Birkett, 2004). Besides the irregularities and inconsistencies of gauge measurements, acquiring gauge data can be difficult due to government policies and bureaucracies. Thus, time series of lake levels covering the period from 1993 to 2015 were downloaded from www.pecad.fas.usda.gov/cropexplorer/globalreservoir database and used in this study to recover water storage changes over Lake Volta during the 2002–2014 period. As reported in Swenson and Wahr (2009), satellite altimetry data has been successfully validated by comparing altimetric time series and in situ observations. Further, the hydrological condition of the Lake Volta was characterised by combining the annual lake variations (1993–2015) with the stream flows of the Volta river system and the Akosombo dam (Section 3.3).

3.3. In-situ river discharge

Monthly river discharge rates observed at the Senchi hydrological station, which is downstream of the Akosombo dam in Ghana were also used in the study. The data, covering the period from 1979 to 2012, was obtained from the Water Research Institute of

Table 1
Details of the stream flow records of the Volta river system (i.e., the White Volta, Black Volta, and Oti rivers) retrieved from the GRDC archives.

River	GRDC no	Latitude	Longitude	Area (km^3)	Station	Duration
White Volta	1531450	9.70	−1.08	92950	Nawuni	1986–2007/02
Oti	1531800	9.28	0.23	58670	Sabari	1996–2007/02
Black Volta	1531050	10.63	−2.92	93820	Lawra	1990/03–2007/02

Ghana. Here, the data, which has no missing record is used as an auxiliary information to investigate the impact of climate variability in the vicinity of the Lake Volta. Also, the river discharge data from the Global Runoff Data Centre (GRDC) (see, www.bafg.de/GRDC), for the three rivers (Black Volta, White Volta and Oti rivers) that drain into Lake Volta have been retrieved and used as a complementary data to support the analysis of hydrological variability of the basin. The White Volta and the Oti rivers are mostly referenced in the manuscript since they contribute more to Lake Volta compared to the Black Volta river. Although the data from these rivers have gaps and missing values, they have been used to support our analysis of the impact of climate variability on the Volta reservoir system. Further details on the GRDC stream flows of the three rivers, which are usually referred to as the Volta river system in the manuscript have been highlighted in Table 1.

3.4. Global Precipitation Climatology Centre (GPCC)

GPCC (Schneider et al., 2014; Becker et al., 2013) product, which provides quality controlled monthly gridded data sets of global land-surface precipitation were used. The gridded precipitation products were accessed through the GPCC download site (www.ftp.dwd.de/pub/data/gpcc/html/downloadgate.html). The $0.5^\circ \times 0.5^\circ$ GPCC data covering the period from 1979 to 2014 was applied in the study to analyse seasonal rainfall variability in the region. Also, the impacts of rainfall conditions on the observed lake level variations from satellite altimetry and in-situ river discharge (Volta river system and Akosombo dam) were investigated using the GPCC precipitation product. Specifically, the long term GPCC based precipitation was combined with river discharge data and satellite altimetry derived water levels to study the hydrological behaviour of the basin.

3.5. Global Land Data Assimilation System (GLDAS)

GLDAS (Rodell et al., 2004) data, which simulates various fields of land surface states and fluxes was obtained from the Goddard Earth Sciences Data and Information Services Center (GESDICS) (http://grace.jpl.nasa.gov/data/gldas/). The NOAH monthly total water storage content (TWSC) of GLDAS, covering the years 2002 to 2013 at $1^\circ \times 1^\circ$ spatial resolution was used in this study to account for the lost signals in GRACE-derived TWS caused by filtering, similar to previous studies (e.g., Landerer and Swenson, 2012). Since GRACE observations will have to be filtered before use in order to reduce noise in the high degree and order Stoke's coefficients (Belda et al., 2015), accounting for the signal damping resulting from the filtering is necessary to benefit hydrological applications. To account for signal attenuation in the filtered GRACE solution, the regularization filter of Kusche (2007) was applied to the gridded GLDAS TWSC in order to derive a synthetic signal that reflects the inherent impact of the filter. This signal, which was thereafter compared with the unfiltered synthetic signal through a least square minimization procedure, resulted in a spatially distributed (grid-based) scale factor that was applied to the filtered GRACE solutions similar to previous studies (e.g., Landerer and Swenson, 2012). The derived scale factor is independent of the GRACE-derived TWS as it is based on simulated TWS changes and does not match the GRACE-derived TWS to those of GLDAS, rather it only restores the relative amplitude of the 'original' data (e.g., Andam-Akorful et al., 2015; Ferreira et al., 2013; Landerer and Swenson, 2012). Consequently, the resulting GRACE solutions can be averaged over arbitrary regions (e.g., the Volta basin) and compared to other gridded data (e.g., precipitation) without having to apply the regularization filter to that data in the spherical harmonic domain (see, Landerer and Swenson, 2012).

3.6. MODIS global terrestrial evapotranspiration project

The MODIS global terrestrial evapotranspiration (ET) products (Mu et al., 2011) was combined with precipitation in this study to estimate net precipitation, a measure of the maximum available renewable freshwater resource. The data, which has a spatial resolution of $0.5^\circ \times 0.5^\circ$ covers the period 2000–2014 and is available for download at the Earth Observing System of NASA's website (http://www.ntsg.umt.edu/project/mod16). The MODIS-derived ET estimates indicated relatively lower magnitude of uncertainties over the Volta basin compared to estimates from GLDAS and terrestrial water budget (see, Andam-Akorful et al., 2015). Hence, the MODIS-derived ET was used to estimate net precipitation over the basin. In this study, trends in the monthly grids of MODIS-derived ET over the LVRB were estimated using a least square method.

4. Method

4.1. Lake Volta induced TWS changes

Observed trends in TWS in the Volta basin are dominated by TWS changes induced by Lake Volta water level changes and the

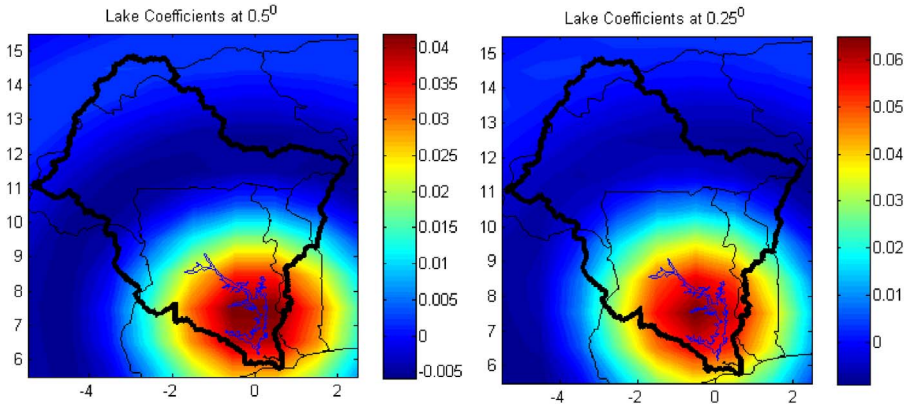

Fig. 3. Lake kernel functions for Lake Volta (blue polygon is the Lake's boundary) whose surface extent of 8500 km^2 was used for the synthesized mask. A grid mask constructed at grid intervals of 0.5° × 0.5° (left) was compared with a grid mask constructed at 0.25° × 0.25° (right). Although the spherical harmonic expansion which is restricted to degree and order 60, similar to GRACE monthly spherical harmonic coefficients, affects the representation of the Lake's extent, uncertainties in the residual water storage over the Lake is somewhat reduced using a grid mask of 0.25° × 0.25°. The solid black polygon is the basin boundary. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

lower Volta where the Volta river system converges. This signal (Lake Volta water level changes) could result in a biased assessment of water storage changes over the entire basin as observed trends in TWS changes of the basin are predominantly from the vicinity of Lake Volta due to water impoundment in the Akosombo dam (i.e., besides that of the lower Volta). In order to remove the Lake Volta signal (i.e., water storage changes due to variations in the Lake's surface) from the observed GRACE-derived TWS, the Lake Volta water level variations were converted to mass changes expressed in terms of TWS following similar approaches in recent studies (see, e.g., Ferreira and Asiah, 2015; Moore and Williams, 2014; Awange et al., 2014). Consistent with other case studies above, a constant surface is assumed over the Lake since the impact of the tidal gravitational force on it can be assumed to be negligible, even despite the shrinking and swelling of the Lake's surface during dry and wet seasons. Consequently, the derived surface water storage (i.e., altimetry water storage) over the Lake would be an approximation given its relatively small size, and the nature of its north-south orientation (cf. Fig. 1). To this end, a global grid mask was defined by a lake kernel function f_{Lake} (Fig. 3) using the geodetic coordinates of the Lake extent as

$$f_{\text{Lake}}(\varphi, \lambda) = \begin{cases} 1, & \text{Over Lake Volta} \\ 0, & \text{Outside Lake Volta,} \end{cases} \tag{3}$$

where φ is geodetic latitude and λ the geodetic longitude. This global grid mask is constructed at grid intervals of 0.25° × 0.25° to adequately capture the lake's shape. A value of 1 was assigned within the Lake surface and 0 outside the Lake. These values are assumed to correspond to 1 mm and 0 mm of EWH over the inland water and elsewhere, respectively. The spherical harmonic synthesis used in the study is based on the Neumann's method, which like the approximate quadrature method fits into the general framework of a weighted least-squares formulation of global spherical harmonic analysis (Sneeuw, 1994). Using the global spherical harmonic analysis, a grid integrable function $f(\varphi, \lambda)$ on a sphere can be synthesized into harmonic coefficients $C_{l,m}$ and $S_{l,m}$ as (e.g., Sneeuw, 1994)

$$\begin{Bmatrix} C_{l,m} \\ S_{l,m} \end{Bmatrix} = \frac{1}{4\pi} \int\int_{\sigma} f(\varphi, \lambda) P_{l,m}(\sin\varphi) \begin{Bmatrix} \cos m\lambda \\ \sin m\lambda \end{Bmatrix} d\sigma, \tag{4}$$

where $d\sigma = \sin\varphi \, d\varphi \, d\lambda$ and $P_{l,m}$ is the normalized associated Legendre function of degree l and order m. Since GRACE fields are snapshots of the static geoid given in terms of spherical harmonic coefficients, the Lake's function $f_{Lake}(\varphi, \lambda)$ (Eq. (3)) is reconstructed (Eq. (4)) and expressed through a spherical harmonic expansion as (e.g., Moore and Williams, 2014)

$$f_{\text{Lake}}(\varphi, \lambda) = \frac{1}{4\pi} \sum_{l=1}^{l_{\max}} \sum_{m=0}^{l} (C_{l,m}^{\text{Lake}} \cos m\lambda + S_{l,m}^{\text{Lake}} \sin m\lambda) P_{l,m}(\sin\varphi), \tag{5}$$

where $C_{l,m}^{\text{Lake}}$ and $S_{l,m}^{\text{Lake}}$ are the dimensionless lake spherical harmonic coefficients. The use of spherical harmonic representation in estimating water storage over lakes is a standard procedure evident in specific case studies listed above. The main essence of this approach as applied in the Volta basin is to help us recover the time series of TWS over the basin that is not associated with Lake Volta. For the Volta basin, these time series mostly would represent changes in groundwater, wetlands, and other small and medium scale reservoirs. The estimated spherical harmonic coefficients $C_{l,m}^{\text{Lake}}$ and $S_{l,m}^{\text{Lake}}$, which were derived by spherical harmonic synthesis up to degree and order 60, are used to recover the time series of the Lake induced TWS (altimetry water storage). The truncation of spherical harmonic coefficients at degree and order 60 is consistent with the CSR RL05 GRACE monthly fields used in this study. Thereafter, each field was scaled by using the time series of USDA altimetry-derived water level variations (previously converted to millimeters). This was achieved by multiplying the changes in the altimetry height with the synthesized kernel function (Fig. 3), which represents the relative sensitivity of GRACE to a unit of water over the lake (e.g., Moore and Williams, 2014). Thus, GRACE-

derived TWS over the Lake was simulated by converting lake level changes from altimetry to water storage changes. To remove the contribution of the Lake from the GRACE observed TWS over the basin, the Lake induced TWS changes (altimetry water storage) were subtracted from the observed TWS over the entire basin.

4.2. Statistical decomposition of TWS

For the statistical decomposition of GRACE-derived TWS into spatial and temporal components, we used the independent component analysis (ICA), a higher order statistical technique that decomposes multivariate data into statistically independent patterns (see, e.g., Cardoso and Souloumiac, 1993; Cardoso, 1999). The method, which has emerged as a complement to principal component analysis (PCA, e.g., Jolliffe, 2002; Preisendorfer, 1988), explores the unknown dynamics of a system through the rotation of the classical empirical orthogonal functions (Aires et al., 2002). ICA has shown great skills in geophysical signal separation (see, e.g., Boergens et al., 2014; Frappart et al., 2011) and spatio-temporal drought analysis (Ndehedehe et al., 2016b). As highlighted earlier, the strong GRACE hydrologic signals of Lake Volta dominates the observed trends in TWS changes over the Volta basin. The Lake's signal was removed and ICA was employed to localise the space-time hydrological signals over the basin. ICA was also applied on TWS changes over the basin before removing the Lake signal in order to examine the dominant patterns and the impact of removing the Lake induced TWS on the total variability of TWS over the basin. The ICA method is based on the JADE (Joint Approximate Diagonalisation of Eigen matrices) algorithm fully described in Cardoso and Souloumiac (1993). The JADE approach exploits the fourth order cumulants of the data matrix (Cardoso, 1999). These cumulants are formed through the process of empirical orthogonal function and diagonalised in order to find a rotation matrix that solves the optimization problem (Cardoso and Souloumiac, 1993). The regionalization (signal localization) process of JADE employs an optimization method to diagonalize the cumulant matrices based on a Jacobi technique (an iterative technique of optimization over the set of orthonormal matrices) (Cardoso, 1999). From the JADE approach (Cardoso and Souloumiac, 1993), the fourth-order cumulant tensor provides the suitable matrices to be diagonalized, which are non-Gaussian (e.g., Ziehe, 2005; Cardoso, 1999):

$$\mathbf{C}_{i,j}(\mathbf{M}) = \sum \mathbf{M}_{u,v}\ \mathrm{cum}(x_i, x_j, x_u, x_v), \tag{6}$$

such that **M** is an arbitrary matrix. After the eigen decomposition of the centered covariance data matrix (e.g., Ndehedehe et al., 2016b), the JADE algorithm performs an approximate joint diagonalisation of the set of eigen matrices of the cumulant tensor with an orthogonal transformation, which comprises a sequence of plane rotations (see, e.g., Ziehe, 2005; Cardoso and Souloumiac, 1993). Further mathematical details on the cumulant-based methods are provided in the pioneering works of Cardoso and Souloumiac (1993), Common (1994), Cardoso (1999). Also, applications of the JADE technique have been well documented (see, e.g., Ndehedehe et al., 2016b; Ziehe, 2005; Theis et al., 2005; Forootan and Kusche, 2012). In this study, use is made of the JADE technique (algorithm available at http://perso.telecom-paristech.fr/cardoso/Algo/Jade/jadeR.m) to decompose GRACE-derived TWS, $\mathbf{X}_{TWS}$ into spatial maps **S**, and temporal patterns **T** (i.e., after removing the water storage contributions from Lake Volta) as:

$$\mathbf{X}_{\mathrm{TWS}}(x, y, t) = \mathbf{TS}, \tag{7}$$

where (x, y) are grid locations (e.g. geographic coordinates) and t is the time in months. **T** is unit-less since it has been normalised using its standard deviation while the corresponding spatial patterns **S**, have also been scaled using the standard deviation of its independent components (i.e., **T**). **T** and **S** are interpreted together and integrated to form what is traditionally called the ICA mode of variability.

4.3. Terrestrial stored water of the Volta basin

GRACE measures vertically integrated water storage that sums up to changes in total hydrological quantities. For the Volta basin, changes in these quantities are given as

$$\Delta\mathrm{TWS} = \Delta\mathrm{SW} + \Delta\mathrm{SM} + \Delta\mathrm{GW} + \Delta S_T, \tag{8}$$

where ΔSW is the change in total surface water storage (i.e., Lake Volta and the rivers), ΔSM is the change in soil moisture, ΔGW is the change in groundwater, and ΔS_T is the change in unquantified surface waters in wetlands and vegetation. After removing the contribution of $\Delta SW_{Lake\ Volta}$ (i.e., the Lake induced TWS signal), the residual water storage change component, ΔW_T is expressed as

$$\Delta W_T = \Delta\mathrm{TWS} - \Delta\mathrm{SW}_{\mathrm{Lake\ Volta}}. \tag{9}$$

This quantity (i.e., ΔW_T), which is the summation of ΔGW, ΔSM, and ΔS_T was statistically decomposed using the ICA method (see Section 4.2) in order to understand its dominant spatio-temporal patterns over the basin.

4.4. Multiple Linear Regression Analysis (MLRA)

The strongest signals in rainfall variability over the Volta basin emanates from the annual and semi-annual signals of the data, hence the annual and semi annual components of GPCC based precipitation were removed in order to understand the impacts of climate variability on the basin. This was achieved by using a multiple linear regression analysis (MLRA) model that parameterizes the trends, cosine, and sine harmonic components. The dataset $\mathbf{Y}_{Rainfall}$, is parameterized as

$$\mathbf{Y}(i, j, t) = \beta_0 + \beta_1 t + \beta_2 \sin(2\pi t) + \beta_3 \cos(2\pi t) + \beta_4 \sin(4\pi t) + \beta_5 \cos(4\pi t) + \varepsilon(t), \tag{10}$$

where (i, j) are the grid locations, t is the time in months, β_0 is the constant offset, β_1 is the linear trend, β_2 and β_3 accounts for the annual signals while β_4 and β_5 represents the semi-annual signals and ε the error term. The deseasonalized data $\mathbf{X}_{Rainfall}$, is characterised as

$$\mathbf{X}_{\text{Rainfall}} = \mathbf{Y} - [\beta_1 t + \beta_2 \sin(2\pi t) + \beta_3 \cos(2\pi t) + \beta_4 \sin(4\pi t) + \beta_5 \cos(4\pi t)]. \tag{11}$$

The deseasonalize GPCC data was then standardised using its standard deviation after removing the mean (see Section 4.6). This is done in order to investigate the relationship between extreme rainfall conditions and the behaviour of discharge at Akosombo and water level variations over the Lake. This should lead to improved understanding of the Lake's hydrology and the impacts of climate variability and human related influence.

4.5. Trend and extreme analysis

A least squares fit was employed to estimate the trends in (i) the time series of averaged residual TWS (after removing the Lake induced water storage) for the period during 2002–2014, (ii) the temporal evolution of independent modes derived from residual TWS decomposition using the ICA method, (iii) time series of the lake height variations after removing the long term mean, and (iv) the gridded precipitation, evapotranspiration and TWS (before and after removing the Lake induced water storage) data sets. The Students' *t*-statistic was used to determine whether the trend was statistically significant (i.e., at 95% confidence level). Furthermore, the trends in the time series of annual maximum and minimum of rainfall, river discharge, and Lake Volta water levels were explored as it is also possible that the impacts of rainfall and river discharges on the Lake (or the influence of rainfall on the Volta river system) may not always be reflected in the mean but instead through changes in the extremes.

4.6. Standardised anomalies

Monthly anomalies for GPCC-based precipitation, river discharge, and the lake height variations were calculated by subtracting the monthly time series of each of these hydrological quantities from their respective monthly mean climatology as

$$\Delta A_i = X_i - \frac{1}{n} \sum X_i, \tag{12}$$

where ΔA_i are the monthly anomalies, X_i is the monthly variable of hydrological quantity of interest, i is the month, and n is the total number of months considered. Furthermore, the monthly anomalies of rainfall, lake levels, and river discharge of Akosombo were aggregated to yearly values and then the cumulative rainfall departure (CRD) (Weber and Stewart, 2004) and cumulative river discharge departure (hereafter called CRDD) were computed. Besides its utility in a predictive capacity, that is, when combined with comprehensive water budget analysis, according to Weber and Stewart (2004), the CRD may be very helpful when employed as a general indicator of rainfall trends, with the upward and downward gradient indicating relatively a rise and decline in rainfall, respectively. Note that the CRDD is computed in a similar way to the CRD and is also employed to evaluate trends in river discharge against rainfall. To further understand the water fluxes and the hydrology of the Lake Volta area, lake levels, river discharge, and TWS with CRD were compared. The annual anomalies of the Lake Volta, Akosombo and the White Volta river stream flow records were standardised and used to study the hydrological condition of the Lake. The value of one standard deviation was used to set the limits for the groupings of the hydrological conditions (Table 2), which is similar to the range of variability approach (RVA) and standardised precipitation index (see, Genz and Luz, 2012; McKee et al., 1993).

5. Results and discussion

5.1. TWS changes induced by Lake Volta water level changes

The discussion in this section focuses on the results of satellite altimetry-derived water storage changes of Lake Volta and residual TWS changes over the Volta basin. The water impoundments at Lake Volta by the Akosombo dam impacts on GRACE-derived TWS changes (hydrological signal), leading to artifacts in the observed TWS trends over the Volta basin. This hydrological signal induced

Table 2
The classification system of hydrological conditions of the Lake Volta based on the annual anomalies of lake water level and stream flow records of the Akosombo station, White Volta and Oti rivers.

Description	Hydrologic condition class
Very wet	> 1.5
Wet	+0.5 to +1.5
Average	−0.5 to +0.5
Dry	−0.5 to −1.5
Very dry	< −1.5

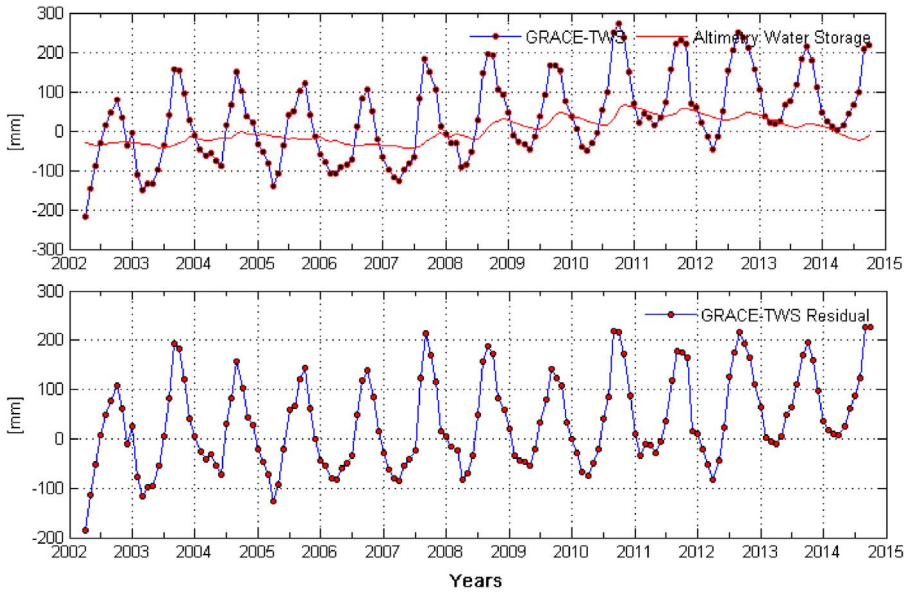

Fig. 4. GRACE-derived TWS changes and altimetry-derived water storage changes (i.e., surface water variability) induced by Lake Volta and the corresponding basin. Top panel: Time series of averaged GRACE-derived TWS over the Volta basin and altimetry-derived water storage changes over the Lake for the common period (2002–2014). Bottom panel: Time series of averaged GRACE-derived TWS over the Volta basin after removing the water storage contributions of Lake Volta.

by water level changes of the reservoir (i.e., Lake Volta), could be misleading and can adversely impact on our knowledge of the hydrological processes in the Volta basin. To understand the temporal hydrological changes in the Volta basin, the Lake Volta TWS change (derived from satellite altimetry water level changes via the method outlined in Section 4.1) is removed from the averaged TWS over the basin to obtain the residual TWS (i.e., ΔW_T in Eq. 9).

Over the basin, the linear trends over a common time period (i.e., between 2002 and 2014) for TWS (i.e., GRACE-TWS, Fig. 4, top) and residual water storage changes (i.e., GRACE-TWS residual, Fig. 4, bottom) were compared to understand the Lake's contribution to the overall trend in the basin. The water storage over the Volta basin (i.e., GRACE-TWS and GRACE-TWS residual) both indicate an increasing trend over the period investigated (see top and bottom panel, Fig. 4). Specifically, GRACE-TWS (i.e., ΔTWS) indicate a monthly trend of 13.96 $\pm$ 2.02 mm, which is about 5.83 km^3 of water over the basin during the 2002–2014 period, while GRACE-TWS residual (i.e., ΔW_T) show a monthly increase of 8.15 $\pm$ 1.3 mm (i.e., 3.40 km^3 of water). The difference between the two trends provides an indication on the contribution of the Lake, i.e., about 5.81 mm/month around the vicinity of the Lake. This contribution (i.e., the trend from the Lake's water storage) amounts to approximately 41.6% of the trend in water storage over the basin for the period between 2002 and 2014. It is fundamentally important to note that the observed trend in TWS over the Lake also depends on the amount of evaporation and rainfall over the Lake. Evaporation and rainfall amounts over the Lake also determine largely not only the Lake's contribution to the observed trend in TWS but also the net flow at the Akosombo dam. This in turn affect the overall trend and amplitudes of TWS change in the basin, as TWS is largely determined by the balance between precipitation and sink terms (river discharge and evapotranspiration). Also, in regard to the synthesized water storage over the lake, the study is also leery of the fact that the Lake's shape (i.e., arborescent with a north-south orientation) may somewhat contribute to uncertainties in the estimated water storage trend over the reservoir. Theoretically, the representation of the Lake's boundary in a spherical harmonics domain, affect significantly the amount of surface water storage recovered from the Lake, owing to the truncation at degree and order 60 similar to GRACE coefficients. Hence, the trend in altimetry water storage (Fig. 4, top) is interpreted with some caution. Nonetheless, our empirical approach to disengaging the Lake induced water storage, allows the understanding of the natural hydrological variability or behaviour of the Volta basin. In the view of increasing attention to the impacts of climate variability, this will be helpful and instructive.

Furthermore, the water storage changes over the Lake (i.e., altimetry water storage) during the 2002–2004 and 2006–2008 periods show deficit conditions (Fig. 4, top). These periods (especially 2002/2003 and 2006/2007) are generally consistent with droughts in the region (e.g., Ndehedehe et al., 2016c; Bekoe and Logah, 2013). More than that, the residual TWS over the basin is instructive of the non-linear hydrological response of the basin (Fig. 4, bottom). The peak amplitude of residual TWS in 2003 is somewhat similar to those of 2007, 2010, and 2012 in the basin, and does not suggest water deficit compared to the observed peak amplitude of TWS in 2002 (Fig. 4, bottom) that indicates the lowest during the 2002–2014 period. Rather, the precipitation deficits during the 2001–2002 period (Section 5.3), resulted in considerable low stream flows of the Oti and Volta rivers (White and Black Volta rivers), which affected the water level of the reservoir in 2003 (Fig. 2). As would be expected, the limited stream flows of the Volta rivers resulted in water deficit in the Lake (i.e., the altimetry water storage) between 2002 and 2004 (Fig. 4, top). Also, the impact of precipitation deficits on the Oti and Volta rivers largely accounts for the deficit conditions in altimetry water storage between 2006 and 2008 (Fig. 4, top). However, the improved rainfall condition of 2003 impacted on the Volta basin leading to a

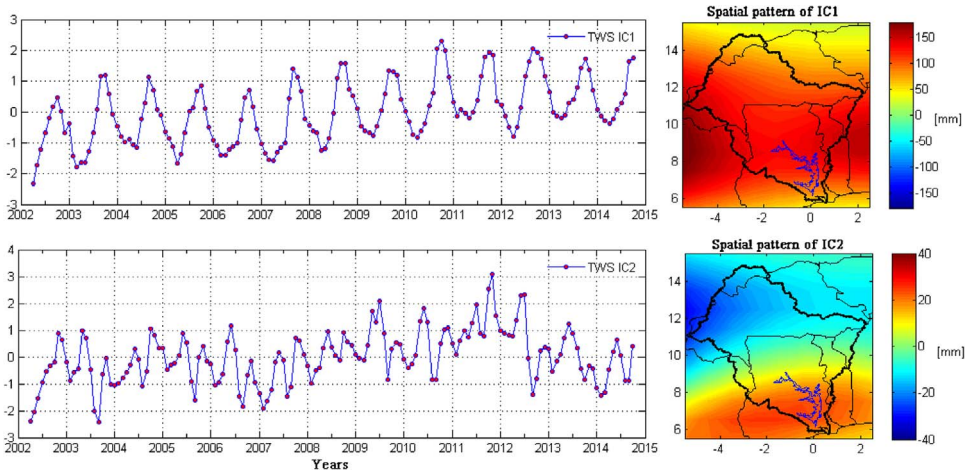

Fig. 5. Independent Components of TWS over the Volta basin (i.e., before removing the Lake Volta signal). These independent components are unitless since they have been standardised using their standard deviations. The spatial patterns (right) are scaled using the standard deviation of the computed independent components (left).

relatively strong peak amplitude of residual TWS (i.e., GRACE-TWS residual, Fig. 4, bottom). Interestingly, strong peaks in residual TWS over the basin are consistent with those of rainfall while strong peaks in altimetry water storage (i.e., Lake Volta) are largely related to strong peaks in stream flows of the Volta river system. This and other intricacies around the basin's hydrology are discussed further in the manuscript (Sections 5.3–5.5).

5.2. Hydrological characteristics based on TWS changes

Contrary to Section 5.1, this section provides further hydrological analysis of the Volta basin by employing the ICA technique to analyse residual GRACE-derived TWS changes (i.e., after removing the contributions of the Lake Volta). In this Section, results of statistical decomposition of TWS changes and residual TWS changes ΔW_T over the basin are discussed further, essentially to better understand the hydrology of the region and to also find a hydrological rationale and scientific justification for the behaviour of observed TWS changes during periods of reduced rainfall and hydrological drought.

Using the ICA method, GRACE-derived TWS was statistically decomposed into spatial and temporal patterns (before and after removing the Lake Volta induced TWS). Two statistically significant independent modes of TWS variability (i.e., without removing Lake Volta signal) were found. The first mode indicates a relatively strong spatial variability over the entire basin; Ivory Coast, Ghana, Togo, and western Burkina Faso (IC1, Fig. 5), which is the source of the Black Volta while the second mode showed spatial variability around the Lake area (IC2 Fig. 5). IC1 and IC2 of Fig. 5 explained 96.5% and 1.9% variances, respectively from the cumulated variance. While IC1 is driven by inter-annual rainfall variability over the entire basin, IC2 is dominated by hydrological signals around the Lake Volta area mostly emanating from wetlands and smaller rivers. The Lake induced TWS (see Section 5.1) showed a correlation of 0.51 with IC2 of Fig. 5, indicating that at least 50% of the variability in the observed TWS over the Lake is explained by IC2. Their temporal evolutions (IC1 and IC2 of Fig. 5) indicate an increase of 26.0 $\pm$ 4 mm/yr and 2.25 $\pm$ 0.5 mm/yr for IC1 and IC2, respectively when jointly derived from the spatial and temporal patterns. The observed trends in the temporal evolution of TWS (IC1 and IC2, Fig. 5) also include the unquantified water storage in wetlands and smaller coastal rivers, which include Chi-Nakwa, Ochi Amissah, Ayensu, Densu and the Tordzie (see details on the geomophology of rivers in Barry et al., 2005).

After removing the contribution of Lake Volta, the results of the statistical decomposition also show two statistically significant modes of TWS change over the basin. Unlike Fig. 5, the first independent mode shows spatial and temporal patterns of TWS over Ivory Coast, upper Black Volta catchment and the Oti river catchment (explaining about 76.2% of the total variability), which includes Ghana and Burkina Faso while the second independent mode indicates TWS signal in the lower Volta catchment (explaining about 21.5% of the total variability), which is in Ghana (Fig. 6). The first ICA mode indicates an increase of 24 $\pm$ 4 mm/yr in TWS over the basin (IC1, Fig. 6) while a decline in water storage (59.5 $\pm$ 8.5 mm/yr) around the lower Volta between 2007 and 2011, which approximates to a loss of 14.19 km^3 of water in Ghana, is observed in the second ICA mode. This loss coincides with declines in the spatial patterns of precipitation in the lower Volta (Fig. 7a) during the same period (2002–2014). Although evapotranspiration does not indicate declines within the vicinity of the Lake (Fig. 7b) as would have been expected, suggesting the non-linearity of hydrological processes in the tropical transition zone of the basin, the estimated trends in the spatial patterns of TWS (Fig. 7c) over the basin (statistically significant at 95% confidence interval), is consistent with the observed trends in dominant patterns of TWS (IC1, Figs. 5 and 6). The spatial patterns of IC1 of Fig. 6 is a prototype of the estimated residual TWS trend shown in Fig. 7d. After removing the lake induced TWS, which explained about 20% of the TWS signal of the basin (i.e., by comparing the variabilities of the first ICA modes of Figs. 5 and 6), the obscured hydrological signal of the lower Volta basin where the White and Black Volta tributaries of the Volta River system converge (i.e., in Ghana) became obvious.

A careful look at IC2 of Fig. 6 shows that the TWS change over Lake Volta area revolves around latitudes 9° N and 6° N, where the Volta river system is mostly concentrated, in addition to other smaller reservoirs and lakes (e.g., Lake Bosomtwe), river tributaries,

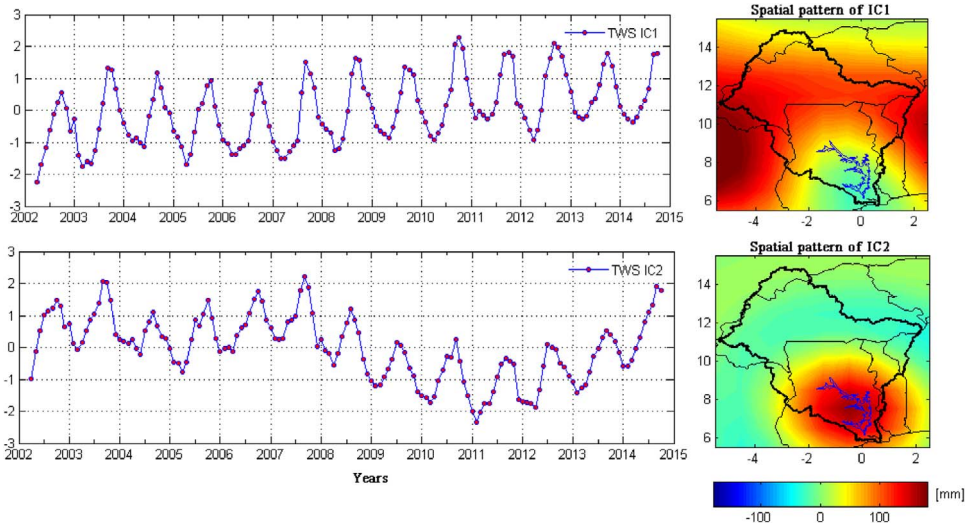

Fig. 6. Independent Components of TWS over the Volta basin (i.e., after removing the Lake Volta induce TWS signal). These independent components are unit-less since they have been standardised using their standard deviations. The spatial patterns (right) are scaled using the standard deviation of the computed independent components (left).

and wetlands. The changes in TWS in this Lake Volta area (IC2, Figs. 6) is largely driven not only by rainfall variability, but also by the annual variability of the three rivers (i.e., the Black Volta River on the west, White Volta river to the east, and the Oti river on northwestern Benin and Togo, see Fig. 1) in Ghana. These rivers, whose flows are high during heavy rainfall periods (e.g., June and July), leading to a high runoff, are the main river systems that drains into Ghana. The loss of stored water at the lower Volta basin in Ghana during the 2007 − 2011 period (IC2, Figs. 6) can also be attributed to the loss of freshwater from these main river systems due to low stream flows and base flow recessions, resulting from precipitation decline during the 2002–2014 period and perhaps human intervention as occasioned by the development and expansion of small and medium scale reservoirs in the basin (e.g., Leemhuis et al., 2009). Since GRACE integrates precipitation over time, base flow recessions resulting from the extended periods of precipitation

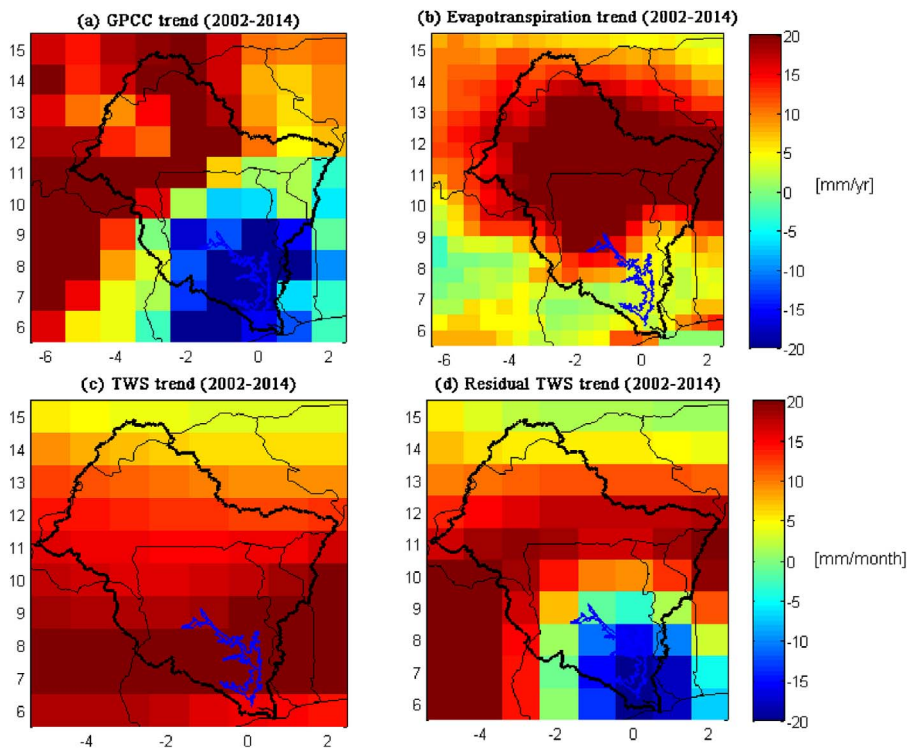

Fig. 7. Trends in water fluxes over the Volta basin during the 2002–2014 period. (a) GPCC based precipitation (b) evapotranspiration (c) GRACE-TWS (i.e., before removing the lake induced TWS) and (d) GRACE-TWS residual (i.e., after removing the lake induced TWS).

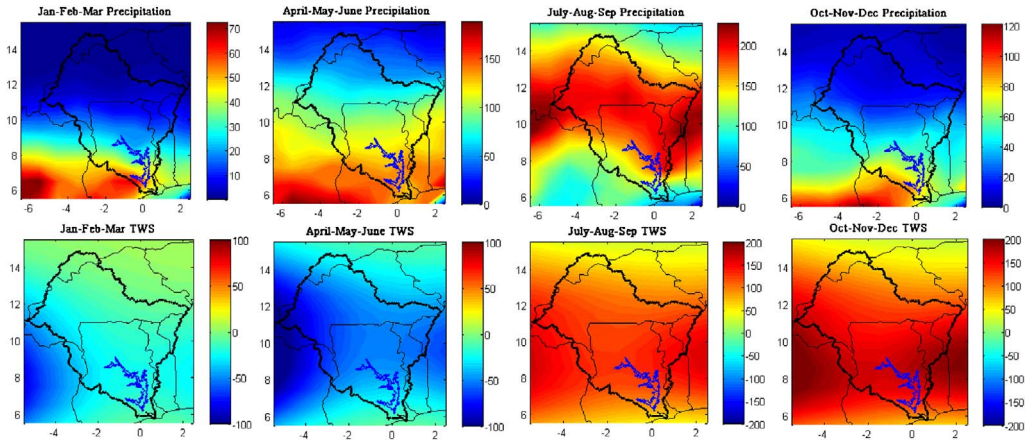

Fig. 8. Seasonal spatial rainfall and TWS patterns over the Volta basin and its surroundings. First row: Seasonal spatial variability of GPCC-based precipitation (2002–2014). Second row: Seasonal spatial variability of TWS (2002–2014).

decline (2002–2014) can cause an extensive temporary storage depletion that are volumetrically significant. However, such storage depletion emanating from an extensive water table decline can be recovered as weather cycles are reversed (see, Alley and Konikow, 2015).

Given the circumstances of increased irrigation schemes and the development of small and medium scale reservoirs within the basin (e.g., Leemhuis et al., 2009; Andreini et al., 2002), one can also argue that the increase in the use of surface water resources in Burkina Faso must have limited the inflow into the lower Volta basin in Ghana, leading to a decline in the observed ΔW_T within that period. Add to this, Leemhuis et al. (2009) presented results that indicated that the expansion of small and medium scale reservoir storage capacity from 0.7 km^3 to 0.79 km^3 during the 1992–2000 period in northern Ghana was related to the storage loss of Lake Volta within the period. With the observed recent decline in Lake Volta water level heights since 2011 till date (Fig. 2), coupled with the observed loss of water storage over the lower Volta (IC2, Fig. 6), the impression is that the Volta basin may be tilting towards drier conditions. However, it is not completely clear if TWS decline (2007–2011) around the lower Volta (IC1, Fig. 6) is strongly linked to the negative trends in rainfall during the 2002–2014 period (Fig. 7a). The sensitivity of lakes, reservoirs, etc., to climate and extreme environmental conditions have been reported (e.g., Ndehedehe et al., 2016a; Deus et al., 2013) and as demonstrated in Section 5.4, the water fluxes of the lower Volta respond to rainfall conditions in the basin with about 1 year lag. While our results in Section 5.3 show relatively drier conditions during the 2011–2013 period (Fig. 9), a recent analysis of spatio-temporal characteristics of hydrological droughts over the Volta basin indicated that the lower Volta area experienced severe drought conditions during the 2010–2013 period (see, Ndehedehe et al., 2016c) (i.e., with respect to the mean of the last four decades). Apparently, rainfall conditions in the western Burkina Faso and the surrounding areas have improved (i.e., showing positive trends – Fig. 7a). Although it is rather empirical than speculative, the negative trends in rainfall patterns around the lower Volta (cf. Fig. 7a) may account for the decline of TWS indicated in IC2, Fig. 6.

However, while it is somewhat becoming drier in recent years around the lower Volta, that is, from the lake levels and the cumulative rainfall departure (see Section 5.4), the rise in TWS during 2011–2014 period in the lower Volta area may be a simple return to 'normal' conditions after the decline in inter-annual variations of TWS during the period between 2007 and 2011 (IC1, Fig. 6). Increased rainfall in 2014 may indicate a reversal of the decline and also a possible return to a normal hydrological state in the lower Volta and the basin at large. This would be consistent with the 4–5 year dry-wet cycle indicated in Sections 5.3.2 and 5.5. As will be highlighted further in Section 5.3.2, observed declines in net precipitation over the basin also coincides with the decline in residual water storage of the lower Volta (IC2, Fig. 6) during the 2002–2014 period. It should be noted that as the hydro-meteorological cycles of the region changes, the loss in water storage changes of the tropical lower Volta are usually recoverable as the hydrology naturally resets to reflect new conditions.

5.3. The response of Volta basin's hydrological system to precipitation

Given that rainfall in the Volta basin translates into a greater proportion of river discharge that feeds the Lake Volta, the stream flow records of the Volta river system (i.e., White, Black, and Oti rivers) were retrieved from the Global Runoff Data Centre (GRDC) archives and analysed. They were combined with flow records of Akosombo and Kpong dams to understand the response of the basin's freshwater systems to rainfall conditions and climate variability. Specifically, all river discharges, lake level variations and TWS were compared with GPCC-based rainfall. As described earlier in Section 4.4, the annual and semi-annual components of GPCC-based precipitation (1979–2014) were removed (deseasonalized) since rainfall in the region is dominated by these components. Removing these components in the time series of the data (e.g., rainfall) allows the examination of peaks and extremes that are perhaps associated with the impact of climate variability. The river discharge data and lake level variation were not deseasonalized but were standardised after removing their long term mean to enhance the evaluation of the sensitivity of the lake level variations and discharge to the vagaries of extreme rainfall conditions over the basin.

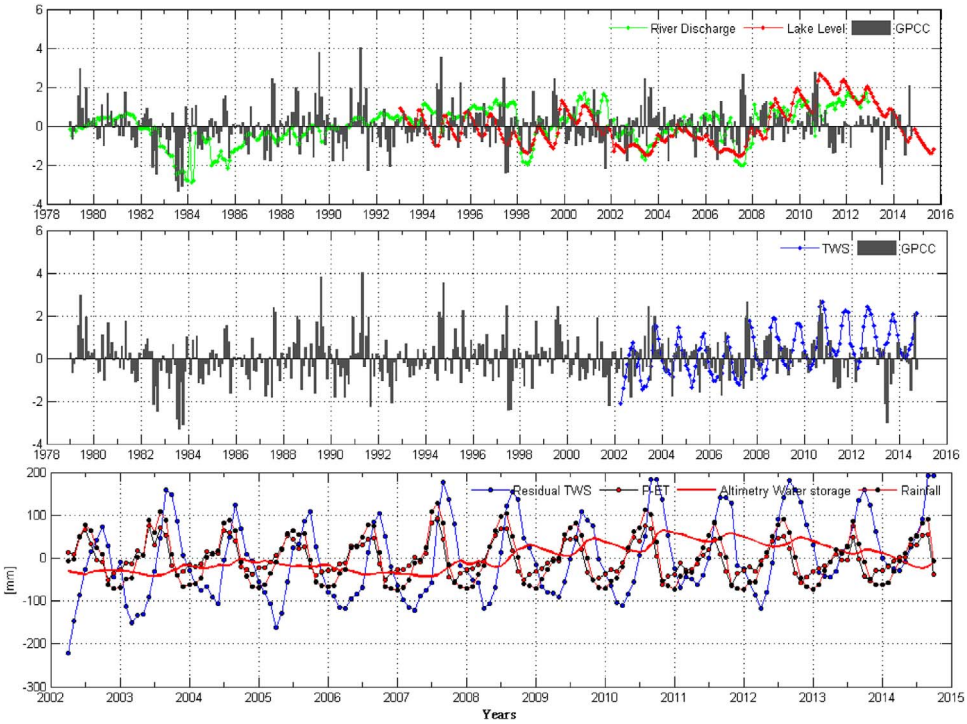

Fig. 9. Relationship between GPCC-based precipitation (extreme conditions) and observed in-situ river discharge and satellite altimetry. The annual and semi annual components of GPCC-based precipitation have been removed using Eq. (10) and then standardised using its standard deviation. Top: Relationship of deseasonalize GPCC (1979–2014) to standardised anomalies (i.e., using their standard deviation) of river discharge at Akosombo (1979–2012), and satellite altimetry-derived water level (1993–2016). Middle: Relationship of deseasonalize GPCC to standardised anomalies of averaged TWS over the Volta basin. Bottom: Time series of net precipitation, residual TWS, altimetry water storage (lake induced TWS) and rainfall anomalies during the GRACE period (2002–2014).

5.3.1. Spatial patterns of seasonal precipitation and stored water

The seasonal rainfall patterns indicate that rainfall is predominant in the July–September period (Fig. 8, row 1) towards the northern part of the basin (upper Volta), where mean rainfall in northern Ghana and Burkina Faso is about 200 mm while it is relatively higher in Ivory Coast/Mali and Benin (not shown). Mean rainfall distribution is more than 200 mm in the upper Volta only during the July-September period while around the lower Volta, mean rainfall distribution for all seasons (except January–March) reaches 120 mm. Areas with observed high seasonal rainfall especially during the July-September period (i.e., Fig. 8, row 1) coincides with relatively high elevation regions such as Ivory Coast and Benin (cf. Fig. 1). Typically, the presence of considerable rainfall can be seen in the southern catchment (lower Volta) all through the seasons unlike the northern catchment (upper Volta) where it is restricted to the April–June and July–September periods.

For TWS, their seasonal patterns show amplitudes of more than 200 mm outside/within the basin area (i.e., in Côte d'Ivoire or Ivory Coast) during the October–December period while the basin area indicates amplitudes of about 150 mm in the spatial patterns of July–August period (Fig. 8, row 2). Comparatively, this is about two months away from rainfall (i.e., indicating a lag of about two months), which shows peaks (strong spatial patterns) in the July–September and April–June periods. The observed strong seasonal TWS spatial patterns in Côte d'Ivoire (Fig. 8, row 2) in the July–September period is that of Lake Kossou, where the hydroelectric power plant is located 16 km upstream of the Bandama river and about 40 km away from Yamoussoukro the administrative capital. We do not dwell on this observed seasonal spatial pattern of TWS in Côte d'Ivoire, as it is outside the Volta basin area. Overall, due to the movement of freshwater from the upper Volta catchment, and the presence of rainfall (usually bimodal in nature) and reservoirs along the coast, large amplitudes of seasonal spatial patterns in TWS are mostly found within the tropical transition zone (i.e., lower Volta). In essence, the large volume of freshwater in the lower Volta is mostly furnished by the upper Volta region, which lies in the Sahel transition zone. This has prominent negative implications for the runoff hydrology of the Volta river system that nourishes the Lake Volta during periods of significant changes in climate. It has been reported that the effects of such periods, for example, rising temperatures and decline in rainfall, are normally felt in areas of hydropower and the negative impact on the morphology of the river estuary (e.g., Gyau-Boakye, 2001).

5.3.2. Precipitation impacts on stream flow at the Akosomobo dam

Since the lack of consistent flow records of the Volta river system limits the overall hydrological assessment of the basin, the stream flow record of Akosombo is explored to assess the impacts of climate variability on the basin. This is possible as the topography and the confined aquifer system of the basin naturally links the Volta river system with the man-made reservoir (Lake Volta, cf. Fig. 1). Generally, relatively dry (e.g., 1983/1984, 1997/1998, and 2013) and wet (e.g., 1991, 1994, and 2010) years are

quite obvious (Fig. 9 top). Lake water level variations and river discharge anomalies responded to the trends of the wet and dry episodes quite well except for 2003 and 2007 (Fig. 9 top). Despite the relatively wet period of 2003 over the entire basin, observed river discharge at Akosombo and the altimetry water levels over Lake Volta indicate extreme negative anomalies, presupposing a dry condition. It seems the extreme dry years of 2001 and 2002 must have prevailed upon the wet period of 2003 leading to strong negative anomalies in river discharge and satellite altimetry water level variations. As there was a rather strong dry (i.e., the rainfall deficiency of 2001 and 2002) period (Fig. 9 top), it took some time for the Lake to respond and also to replenish the TWS in the basin. It can also be argued that, after a wet period, considerable stream flow from the Volta river system reaches the lake after significant proportion of precipitation has been absorbed by the dry areas around the lake's catchment, creating a non-linear response. For instance, the response of river discharge and the Lake to the wet period in 2003 can be seen at the end of 2004 while the wet period in late 2007 after a previous drought period in 2006 can be seen in 2008 and beyond (Fig. 9 top). This implies a time lag of about 12 months or more between an extreme dry period and the time for the Lake to transit into a wet condition.

A recent study over the Volta basin (Ndehedehe et al., 2016c) confirmed this late response of reservoirs and surface water to extreme rainfall conditions. The study showed that standardised precipitation index (SPI) and standardised runoff index (SRI) exhibited inconsistent behaviour in observed wet years over the Volta basin presupposing a non-linear relationship that demonstrates the lag between long term river discharge and precipitation especially after a previous extreme dry period. For instance, Ghana suffered electric power rationing during 1983–1984, 1997–1998, 2003, and 2006–2007 due to hydrological drought (Bekoe and Logah, 2013). However, the limited hydro-power capacity of the Akosombo dam in 2003 that resulted in electric power rationing was not caused by hydrological drought of the year, rather, it was attributed to the effects of previous drought years of 2001 and below average rainfalls in 2002 (Bekoe and Logah, 2013). This observation is consistent with our results that indicate drier conditions in 2001–2002 and relatively wet conditions in 2003 (Fig. 9, top). It should also be pointed out that while the decline in the lake levels between 2014 and September 2015 can be seen as a response to the dry condition in late 2013, the decline of the lake level between 2011 and 2013 could be due to precipitation deficits of 2011 (Fig. 9, top), that is assuming a 12-month lag between rainfall and the inflow of water from the upper Volta basin to the Lake. Of course, the spilling of the reservoir in November 2010 due to increase in annual rainfall totals in most parts of Ghana (see, Owusu and Waylen, 2013) is not left out. Although the amplitudes of TWS and residual TWS over the basin during wet periods of 2003, late 2007, and 2010 are are somewhat consistent with those of rainfall anomalies (Fig. 9, middle and bottom panels), the observed peaks of net precipitation does not capture this unique hydrological periods occasioned by the impact of climate variability. Rather, a net precipitation (i.e., *P–ET*) decline of -15 mm/yr was observed during the period (Fig. 9, bottom), coinciding with the observed decline in residual water storage in the precinct of the lower Volta between 2007 and 2011 (IC2, Fig. 6), and the negative trends in precipitation patterns reported in Section 5.2.

Further, recall that as indicated earlier, Bekoe and Logah (2013) attributed the low hydro-power production of 2003 to the impacts of 2001 drought episode and the below average rainfall of 2002. Likewise, the observed extreme low anomalies of river discharge and altimetry water levels observed in late 2007 (Fig. 9, top) are inconsistent with rainfall in the same period. This behavior demonstrates the general physical hydrological phenomenon within the basin where wet periods are preceded by low water level in the Lake, due to limited rainfall. Generally, this behavior is observed in the wet years of 1994, 1999, 2003, 2007, and 2010, which are preceded by dry periods (Fig. 9, top).

Furthermore, from the standardised rainfall in Fig. 9, it seems there is a 4–5 year cycle between dry and wet periods (the classification of wet and dry periods are based on 1 standard deviation as mentioned in Section 4.6). Again, the consistent low rainfall amplitudes between 2004 and early 2007 and the acknowledged drier conditions of 2006 can possibly account for the pronounced negative anomalies of Akosombo river discharge and altimetry water levels in late 2007. As it will be shown later, it seems the White Volta and Oti rivers contributed to the low amplitudes of the Akosombo discharge. These rivers show a linear relationship with rainfall in the basin and are naturally linked to the tropical transition zone, the lower Volta. The flow regimes of these rivers are however not only affected by the hydraulic characteristics of the region, but may also be influenced by human activities in the basin such as infrastructure watershed development (e.g., Leemhuis et al., 2009). Moreover, observed relationship between TWS and the rainfall over the Volta basin appears to be consistent (Fig. 9, middle). However, the drier conditions of 2013 as shown in the extreme negative anomalies of rainfall in the mid-year is inconsistent with observed TWS change (Fig. 9, middle). We have not identified any potential cause regarding this inconsistency, further discussions on the cumulative annual rainfall anomalies and TWS have been provided in Section 5.4.

5.3.3. Freshwater systems

The major freshwater systems of the Volta basin are basically the White, Black, and Oti rivers (hereafter called the Volta river system) and Lake Volta. The natural variability of these rivers have been compared with flow records of Akosombo and Kpong dams (Fig. 10a), which are meant to manage the reservoir outflow for hydropower purposes. In addition, the relationship of the Volta river system with rainfall variability and the Lake Volta, that is, based on their monthly anomalies have been examined. From visual inspection, the White Volta and the Oti rivers are more related to the Akosombo and Kpong flows (hereafter called dam flows), that is in terms of their lowest minimum peaks (lowest minimum peaks of the White Volta and Oti rivers impact on dam flows). The well known periods of hydrological droughts and water shortage (1983/1984, 1997/1998, and 2006/2007) in the Lake, resulting in low flows (Fig. 10a) during the same periods are consistent with the observed precipitation anomalies (Fig. 10b). More importantly, antecedent conditions and the impact of water carried forward from previous storage is also observed. For instance, extreme low flows of the White Volta and Oti rivers (1997, 2002, and 2005/2006) consistently resulted in extreme low flows of the dams in the year that followed (approximately 12 months). Add to this, while the impacts of the 1997 El-Niño and 1999 La-Niña are reflected in the peak amplitudes of the two rivers, it is further confirmed that 2003 was not a dry year as the rainfall anomalies and the Volta river

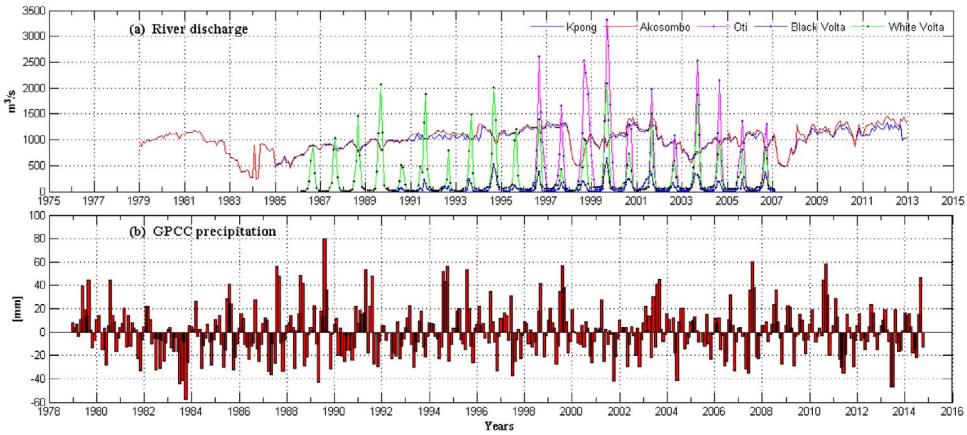

Fig. 10. Influence of precipitation on stream flow records of the Volta river system. (a) Time series of observed river discharge at the Kpong/Akosombo (1979–2012), Black Volta (1990/03–2007/02), White Volta (1986/03–2007/02) and Oti (1996/03–2007/02) rivers. (b) Time series of GPCC based precipitation anomalies over the Volta basin (1979–2014).

system show relatively strong amplitudes of discharge (with maximum Oti river discharge reaching 2500 m^3/s) and rainfall anomalies (Fig. 10a and b). Rather, the rainfall deficits of 2002 (Fig. 10b), which is consistent with the extreme low flows of the the Volta river system (Fig. 10a) caused the water shortage in the reservoir (cf. Fig. 9, top), resulting in limited dam flows.

The Volta river system generally shows a linear response to rainfall, with the White Volta and Black Volta rivers explaining higher variabilities in rainfall (31% and 34%, respectively) compared to the Oti river (Table 3). However, the Oti river is well correlated with rainfall over the basin at 2 months lag. Although the Black Volta is actually a far larger catchment nourishing Burkina Faso and other catchments outside Ghana, the White Volta and Oti rivers contribute more freshwater to the Lake Volta as can be seen in their annual amplitudes (Figs. 10a and 11a–c). According to Andreini et al. (2002), of all the water flowing into Lake Volta, about 67% comes from outside Ghana through the Volta river system, with Oti river contributing the largest share (about 32%) to the Lake. This perhaps explains the observed limited alimentation in the Lake during the 1996–2007 period (Section 5.5), consistent with the declines of 380 $m^3/s/yr$ and 6.96 $m^3/s/yr$ in the Oti and White Volta river flows (Table 3), respectively. Oti river explains about 14% of the changes in rainfall (i.e., $R^2 = 0.14$) compared to the White and Black Volta rivers with relatively higher variabilities (see Table 3 and Fig. 11d–f) while stronger extremes in Oti river flow (e.g., 2003) are also sometimes inconsistent with observed water levels in Lake Volta (Fig. 11c).

Furthermore, unlike the Volta river system, the dam flow records, which do not show natural variability (Fig. 10a) indicate a non-linear response to rainfall due to damming of the rivers. Although the flow records of the Volta river system are missing for the remaining periods studied (i.e., 2007/03–2014), the rising trend of the dam flows after the 2007 La-Niña up to 2010 is consistent with the increasing trend in observed water levels and water storage in the Lake (cf. Fig. 9). Our results confirm that the dam flow records are largely indicative of the Lake's water level, which in turn relies on the Volta river system. As the stream flow records of the Volta river system are incomplete, the dam flows can be combined with rainfall over the basin to provide hydrological information that will support our understanding of the impact of climate variability in the basin. This is further discussed in Section 5.4.

5.4. Cumulative rainfall departure and water fluxes in the Volta basin

Here, the observed relationship between GPCC-based precipitation and water fluxes (specifically the Akosombo river discharge and the satellite altimetry derived water levels) using annual cumulative departures is discussed further. The cumulative rainfall departure (CRD) and cumulative river discharge departure (CRDD) (i.e., annual) indicates a statistically significant correlation of 0.75, suggesting that there is a link between rainfall in the Volta basin and the river discharge at Akosombo (see Fig. 12). Evaluating the relative increase or decrease of river discharge in relation to rainfall, we found that the increase or decline in rainfall was not accompanied immediately by a similar rise/fall in river discharge, indicating that the current Akosombo discharge is influenced by the rainfall conditions of the previous year. For example, the decline of river discharge in 1981/1982 was a response to the rainfall

Table 3
The relationship between precipitation in the Volta basin and the Volta river system (i.e., White Volta, Black Volta, and Oti rivers). Correlations (r) are statistically significant at 95% confidence interval. Trends marked with * are not statistically significant at the 95% confidence interval. The maximum r is with respect to the lags indicated.

River	Correlation (r)	Maximum r	R^2	Lag	Period	Trends ($m^3/s/yr$)
White Volta	0.56	0.75	0.31	1 month	1986/03–2007/02	−6.96*
Oti	0.38	0.80	0.14	2 months	1996/03–2007/02	−380.24
Black Volta	0.58	0.80	0.34	1 month	1990/03–2007/02	27.6*

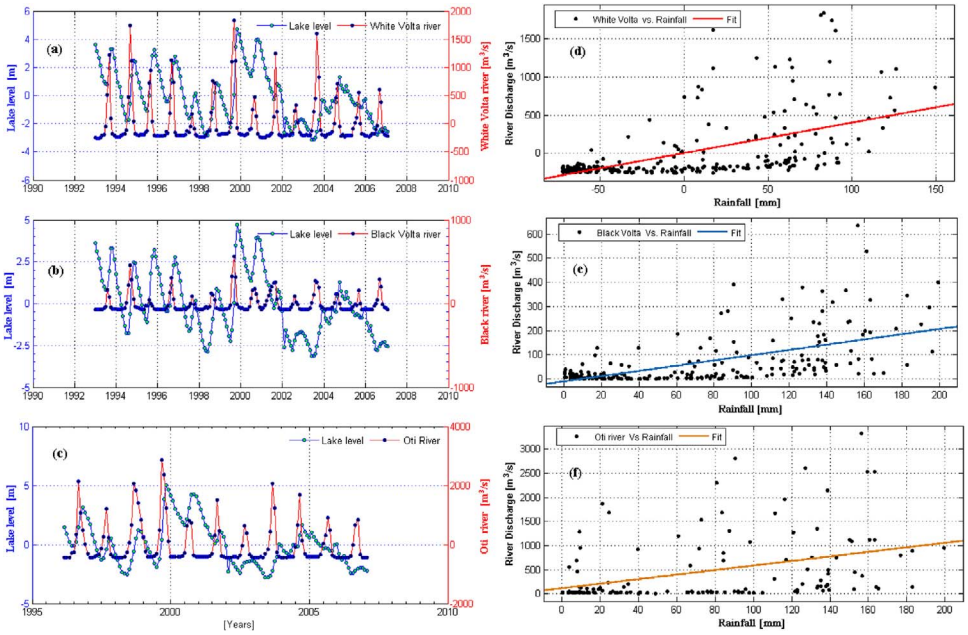

Fig. 11. Relationship between precipitation in the Volta basin and the Lake Volta/the Volta river system. (a)–(c) Time series of Lake Volta water level anomalies (i.e., after removing the mean) and anomalies of White Volta (1993–2007), Black Volta (1990/03–2007/02), and Oti (1996/03–2007/02) rivers. (d)–(f) Regression fits between rainfall and the stream flows of White Volta (1986–2007/02), Black Volta (1990/03–2007/02), and Oti (1996/03–2007/02) rivers. The R^2 values summarising the relationship between precipitation and the Volta river system are provided in Table 3.

decline of 1980 while the increase of rainfall, which started in 2006 was reflected in river discharge in 2007 (Fig. 12), presupposing a lag of 1–2 years or less (i.e., when other time windows are also analysed). This is also consistent with the results discussed previously in Section 5.3. This preceding circumstance (i.e., the time lag) in the observed relationship between rainfall and river discharge, which may not be unconnected with the diversions from the Volta basin watershed and the interconnected Volta river system with numerous tributaries, could be critical information useful for management decisions in water resources planning. The link between rainfall and river discharge (i.e., CRD and CRDD) was also found to be stronger at annual scales compared to monthly scales, which showed a correlation of 0.57 (See Appendix A1 Fig. 16).

Further comparison of lake levels, river discharge, and TWS (i.e., at annual scales) with CRD, generally show the apparent relationship of rainfall and these water fluxes (see Fig. 13). TWS show the strongest association with a correlation of 0.81 with CRD compared to river discharge and lake levels with correlations of 0.42 and 0.57 with CRD, respectively. Such relationship may be

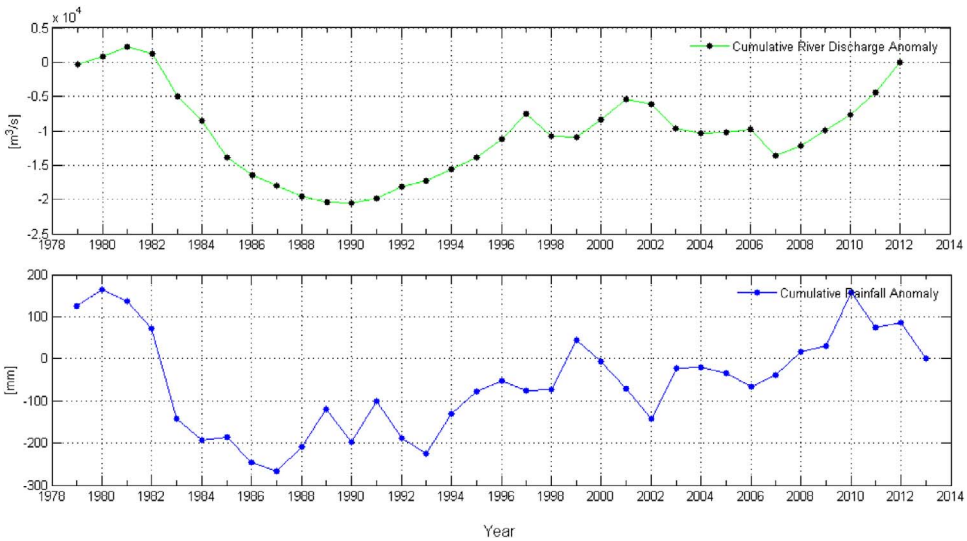

Fig. 12. Cumulative river discharge departure (CRDD) and cumulative rainfall departure (CRD) over Lake Volta basin using the GPCC based precipitation and river discharge at Akosombo station, respectively. Top: Annual cumulative river discharge anomaly over the basin during 1979–2012 period. Bottom: Annual cumulative rainfall anomaly over the basin during 1979–2013 period.

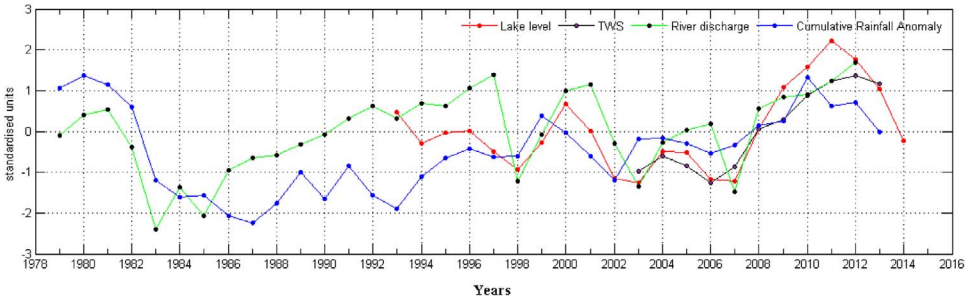

Fig. 13. Comparison of river discharge at Akosombo station, Lake Volta water levels, and change in TWS to cumulative rainfall departures (i.e., using GPCC based precipitation). The standardised annual cumulative quantities of river discharge (1979–2012), lake level variations (1993–2014), and TWS anomalies (2003–2013) over the Volta basin are compared to cumulative rainfall departures (1979–2013).

expected as TWS in the basin is driven mostly by precipitation changes. Although all water fluxes demonstrate a level of significant sensitivity to rainfall conditions in the basin, river discharge and lake levels in particular reveal some reservoir storage characteristics. For example, a close examination of Fig. 13 shows that a rise in river discharge preceded a rise in CRD during the 1984–1986 period while in the case of the Lake Volta water levels, we found that lake level declines prior to a decline in CRD mostly with an approximate time lag of one year (Fig. 13). Besides the diversion of water into other watersheds and tributaries in the Volta river system, which may partly account for this hydrological response, the influence of previous years rainfall largely controls the Lake's current behaviour and by extension the river discharge at Akosombo, which depends on the inflow from the Volta river system into the Lake. This, for example, was the case in 2003 when the lake level and river discharge were extremely low due to extreme dry conditions of the immediate previous years of 2000–2002 (see Fig. 9, top).

However, opening the spillways of the Akosombo dam to let out excess water in the reservoir as was the case in 2010 due to extreme wet conditions in the basin during late 2007 and 2010 periods (e.g., Ndehedehe et al., 2016c), may create an exception to this rule of thumb, given that a fall in CRD from 2010 up until 2013 was accompanied by a rise in river discharge during the same period (see Fig. 13). During low rainfall periods, low water table and diminished base flows are expected. As further explained by Weber and Stewart (2004), when decreased base flows are combined with reduced over-land runoff, it unarguably culminates in lower stream discharge. In our case, the river discharge showed a consistent rise since late 2007 up until 2012 (see top panels of Figs. 9 and 13) even when the CRD had indicated decline since 2010, confirming an excess discharge flow that was inconsistent with rainfall trends in the basin during the 2010–2012 period (see Fig. 9, top).

It has been argued that periods of unusual rainfall caused by climate teleconnection patterns (e.g., ENSO) create the probability of a reset of hydrological conditions through the provision of extensive recharge to aquifers and filling up of existing surface storage (Weber and Stewart, 2004). Consequently, such influence (i.e., extraordinary rainfall) leads to flood conditions in the region (e.g., Paeth et al., 2012) on the one hand, while on the other hand, the aftermath of such stupendous amount of rainfall increases aquifer storage and inundated areas leading to increased TWS changes (e.g., Ndehedehe et al., 2016a). This occurs specifically in regions with high soil infiltration capacity and hydraulic conductivity (e.g., Descroix et al., 2009). Since surface waters, soil moisture, groundwater, and wetlands are the major catchment stores that drives changes in TWS in the Lake Volta area (i.e., around the lower Volta basin), the water ponding and spilling of Akosombo is likely to create a provisional or spurious trend in TWS. This is one reason why the TWS (i.e., with the Lake induced TWS) over the basin also indicated a rise during the 2010–2012 period, consistent with river discharge during the same period despite the apparent fall in CRD since 2012 (Fig. 13). To buttress further on the impacts of the Lake on TWS over the basin, when it was separated (see Section 5.1), interestingly, a close inspection revealed that the Lake-induced TWS (see Fig. 4 top), which is usually triggered by annual and seasonal rainfall over the basin indicated a decline during 2010–2014 period, consistent with CRD and the lake level (Fig. 13). However, between 2012 and 2013, it seems there was a reset of hydrological conditions as both the CRD and TWS indicated a fall (Fig. 13), consistent with the lake level, which also indicates a fall during the same period (Fig. 13).

5.5. Hydropower reservoir system of the Lake Volta and the impact of climate variability

The concept of stationarity assumption in hydrological time series is said to have been compromised by human activities in river basins (Genz and Luz, 2012). The construction of dams and land use change, for example, apart from contributing to non-stationarity in hydrological time series (e.g., Ngom et al., 2016; Descroix et al., 2009; Leblanc et al., 2008), amplifies natural climate changes, environmental conditions (e.g., increase in Hortonian runoff due to changes in infiltration capacity), and the impacts of atmospheric circulations and low frequency internal variability. This is the case for the Volta basin, where the flow records (not shown) of the Volta river downstream Akosombo during the 1936–1966 period indicate natural variability consistent with precipitation changes in the pre dam construction era, unlike the post dam era, where the generation of flows at Akosombo are the results of water management strategy. After the damming of the river at Akosombo, not only has there been tremendous changes in the hydrological regimes of the river, the impact of small changes in precipitation leading to large changes in runoff has also been reported (Oguntunde and Friesen, 2006; Friesen et al., 2005). Apart from other known consequence of damming rivers in order to generate hydropower (for example, decline in annual sediment flux and discharge, reservoir aggradations, and water quality degradation) (see,

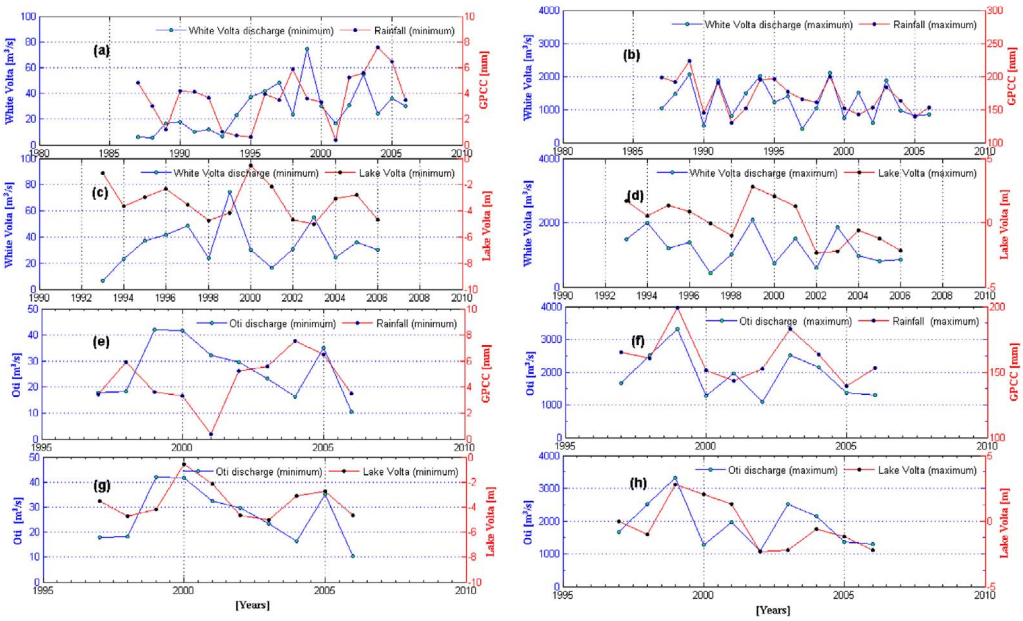

Fig. 14. Analysis of extreme annual rainfall (1986–2006), White Volta river discharge (1986–2006), Oti river discharge (1997–2006), and satellite altimetry derived water levels (1993–2006). (a)–(d) Maximum and minimum White Volta river discharge compared with those of Lake Volta water levels, and GPCC based precipitation over the Volta basin. (e)–(h) Maximum and minimum Oti river discharge compared with those of Lake Volta water levels, and GPCC based precipitation over the Volta basin.

e.g., Fan et al., 2015; Gyau-Boakye, 2001), the impacts of climate variability on water availability in the Lake and the corresponding basin is a critical issue for consideration. In the preceding sections, much about the associations of the Volta river system with rainfall have been discussed. Here, the mechanisms of extremes in rainfall and its link to stream flow (especially the Oti and White Volta rivers) and Lake levels are considered. Most importantly, the hydrological condition of Lake Volta is characterised using annual stream flow of Akosombo and the Lake levels.

5.5.1. Analysis of extremes on the Volta river system and Lake Volta

The statistically significant (i.e., $\alpha = 0.05$) rising trend of 1.66 $m^3/s/yr$ in minimum flow of the White Volta coincides with the increase in rainfall (0.13 mm/yr) in the basin during 1986–2006 period (Fig. 14a). But the observed decline in maximum flow (20.4 $m^3/s/yr$) of White Volta is not statistically significant unlike the decline in maximum rainfall (1.92 mm/yr) during the period (Fig. 14b). Comparing the White Volta and Lake Volta water levels during a common period where both data are available (1992–2006), the trends in their minimum quantities (0.56 $m^3/s/yr$ and -0.1 m/yr, respectively) are not statistically significant (Fig. 14c) while only Lake Volta showed a statistically significant trend (-0.25 m/yr) (Fig. 14d) when the trends of their maximum values were estimated. While rainfall is expected to impact on the generation of flows, their extremes in the Volta basin raises the question of whether observed trends have any connection with human influence. Since the White Volta river nourishes the Lake, the lack of a statistically significant trend in the maximum flow of the White Volta may suggest water loss through evaporation from the Lake's surface. In fact, there has been a unanimous position confirming the extensive loss of water through evaporation from the Lake's surface (see, e.g., Leemhuis et al., 2009; Gyau-Boakye, 2001; Giesen et al., 2001).

Although other existing smaller water infrastructures in the basin contribute to water loss, Leemhuis et al. (2009) emphasized that water losses through evaporation from Lake Volta are three times higher than losses emanating from small and medium scale reservoirs in the basin. Also, given the source of the White Volta (i.e., Burkina Faso) where larger withdrawals of surface water are mainly employed in agriculture as reported by Giesen et al. (2001), the coupled effect of a statistically significant decline in rainfall and human intervention, which restrict the rate of inflow into the Lake, when superimposed on the water loss through evaporation from the Lake's surface are possible reasons that may largely account for the statistically significant decline in maximum lake water levels observed during the period. Changes in evaporation of lakes impact significantly on the energy and water budgets. For instance, in the Lake Volta, Giesen et al. (2001) reported a net precipitation deficit resulting from water budget imbalance between precipitation and evaporation while Gyau-Boakye (2001) attributed the decline in the Lake's water level to observed rising temperatures and diminished runoff from the Volta river system, resulting from precipitation deficits. As shown earlier in Section 5.3.2, during the 2002–2014 period, the observed decline in net precipitation coincides with precipitation decline and loss of water storage in the Volta basin. However, irrespective of the period considered for the trend analysis, the negative trend in maximum rainfall, is consistent with those of White Volta (-41.9 $m^3/s/yr$, though statistically insignificant) and Lake levels.

For the Oti river (Fig. 14, e–h), the trends in the maximum and minimum river discharge (-88.1 $m^3/s/yr$ and -0.82 m/yr, respectively) were negative, consistent with those of Lake Volta water levels (-0.33 m/yr and -0.04 m/yr for maximum and minimum estimates, respectively) and rainfall (only the maximum estimate indicated a decline of -2.0 mm/yr while the minimum

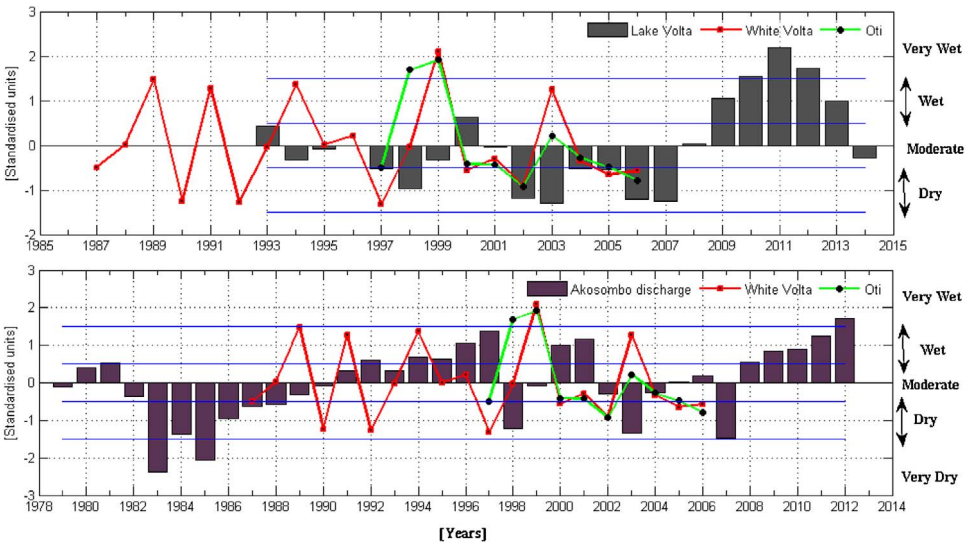

Fig. 15. Recent hydrologic condition of Lake Volta. Top: Time series of annual Lake Volta water level changes (1993–2014), the White Volta (1987–2006), and Oti (1997–2006) rivers. Bottom: Time series of annual Akosombo discharge (1979–2012), White Volta and Oti (1997–2006) rivers. The blue lines define the limits of each hydrological condition class. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

estimate was 0.22 mm/yr) during the common period (1997–2006). These trends were all statistically insignificant ($\alpha = 0.05$) for the different periods evaluated. The observed association between the extremes of the White Volta and Oti rivers with rainfall in the basin and the Lake Volta is however, instructive and revealing. For instance, a negative correlation of -0.42 was observed between minimum White Volta river and the Lake Volta water level (Fig. 14c) while the Oti river showed positive correlation of 0.53 with Lake Volta water level (Fig. 14g). Apart from the hydraulic characteristics of the catchment, this could imply that a large proportion of the minimum flow of the White Volta (possibly due to limited and declining rainfall) does not reach the Lake, as it is likely to be lost in transit or intercepted due to diversions in the watersheds outside Ghana. The maximum flows of these two rivers however indicated positive correlations (0.38/0.38) with the Lake (Fig. 14d and h), consistent with their strong positive correlations of 0.69 (White Volta river) and 0.81 (Oti river) with rainfall (Fig. 14b and f) during the periods considered. Generally, maximum correlations ranging from 0.79 to 0.94 between the two rivers and rainfall were obtained at 1 year lag and less (i.e., their minimum and maximum quantities), consistent with the results in previous sections. This relationship is useful in assessing the alterations in hydrological regime resulting from climate variations.

5.5.2. Recent hydrological conditions of the Lake Volta

To understand the hydrological regimes of the Lake Volta, the flow records of Akosombo and lake water levels were combined with the flow data of the two major rivers that nourish the Lake (i.e., White Volta and Oti rivers). Contrary to Section 5.3.2, the standardised annual anomalies of the Lake have been used to express the hydrological characteristics of the Lake. The standardised annual anomalies of the White Volta and Oti rivers for the available period have also been incorporated to support the discussion in this section. Between 2001 and 2007 it appears the Lake has been consistently dry (Fig. 15, top) compared to the 2009–2013 period that is wet. The dry condition of the 2002–2007 period is consistent with the water storage (i.e. altimetry derived water storage) deficit over the Lake during the same period (Fig. 4, top). After the 1999 La-Niña, which resulted in very wet conditions of the Volta river system and wet conditions in the Lake, the dry (2000 and 2002) and moderate (2001) conditions of the White Volta and Oti rivers have significantly impacted the Lake hydrological condition in 2002 and 2003, resulting in dry conditions (Fig. 15, top), despite the improved rainfall over the basin and the wet conditions of these rivers in 2003 (though the Oti river indicated a moderate condition in 2003 possibly due to the mean of the period analysed). Since mankind naturally responds to variations in climate, the periods of limited flows in the White Volta and Oti rivers must have been exacerbated by human intervention (e.g., irrigation development), owing to increased demand and use of surface water in the basin. This is marginally stated as the impact of climate variability in the basin, (e.g., the low flows of these rivers during 2000–2002 and 2004–2006 periods) appears to be more critical. However, as reported by Smakhtin (2001), human activities such as deforestation and irrigation development have lead to increased frequency of occurrence of low-flow discharges in hydrological regimes of rivers.

Under the global change in the hydrological cycle Volta Project (see, Andreini et al., 2002), the impact of water infrastructures in the Volta basin, such as the development of small and medium scale reservoirs in Burkina Faso and northern Ghana in the early 1970s is known to have initiated the loss of water storage in the Lake Volta (Leemhuis et al., 2009). While the White Volta and Oti rivers indicate moderate and dry conditions during 2004–2006 period, consistent with the Lake (Fig. 15, top), the Lake's water storage, which is also marginally affected by these small water infrastructures during long dry periods, naturally affects the generation of flows downstream Akosombo (Fig. 15, bottom). We note that the difference in the hydrological condition of the Lake (2002–2007) as characterised using the satellite altimetry data (Fig. 15, top) and that of the Akosombo river flow during the same period (Fig. 15,

bottom), could be due to the adopted mean of the Akosombo stream flow, which references the 1979 climatology. Apart from the response of the Lake to incoming flows, which is about 12 months or less, the hydrological rationale for a relationship between river discharge (i.e., the Volta river system) and the Lake's water level spanning a period of 1–2 years is true for the Volta basin. The probable impact of climate variability on the Lake's water level as indicated in the clustering of dry years 2002–2007 and wet years 2009–2013 (Fig. 15, top), appears to be a 4–5 year cycle (cf. Fig. 9, top), consistent with the long term Akosombo stream flow (Fig. 15, bottom). Continuous gauge measurements of the three rivers (White Volta, Black Volta, and Oti rivers) will allow this cycle to be further confirmed and also for the impacts of climate variability and human interventions in the basin to be quantified.

6. Conclusions

The impacts of large water projects such as the Akosombo dam in the Volta river basin and other human interventions have complicated the understanding of natural hydrological variability and the influence of climate variations on the basin's freshwater systems. In this contribution, we have investigated the hydrological variability of the Volta basin (including the Lake Volta) using GPCC based precipitation, river discharge, GRACE-derived TWS, evapotranspiration, and satellite altimetry water level variations. A two-step procedure based on a weighted least squares formulation of global spherical harmonic analysis and statistical decomposition was employed to support the understanding of the Volta basin's natural hydrology and its freshwater systems. The results from this study are summarised as follows:

(1) Increased trends of TWS over the Volta basin and the Lake Volta were observed. The empirical approach adopted to disengage the Lake induced water storage enhanced the understanding of the natural hydrological variability of the Volta basin. In view of the increasing attention to the impacts of climate variability in the region, this information is helpful and instructive for regional water resources management and in addition, provides a basis for productive trans-boundary water sharing conversations.
(2) The statistical decomposition of residual TWS (i.e., after removing Lake Volta induced TWS) resulted in a decline of water storage for the period between 2007 and 2011 at the lower Volta catchment. The loss of water storage during this period could be a base flow recession resulting from precipitation decline during the 2002–2014 period and the extended periods of dry conditions around the vicinity of the Lake between 2000 and late 2007.
(3) Declining trends in recent altimetry-derived water level variations of Lake Volta (2011–2015) are consistent with the decline of rainfall and net precipitation during the 2002–2014 period. This decline is also attributed to the cumulative impact of limited stream flows from the Volta river system. The study also confirms the impact of critical hydrological periods (e.g., previous extreme dry periods) and human water management (e.g., spilling of the reservoir at downstream Akosombo in 2010) on the basin. During these periods, trends in rainfall are usually accompanied with inconsistent trends in lake water levels and discharge flow at Akosombo.
(4) The results also show that extended dry periods as observed between 2001 and late 2007 diminishes the quantity of freshwater that is required to sufficiently satisfy water demand for agriculture (in Burkina Faso) and hydro-power (in Ghana) in the region, such that the extreme wet periods (e.g., 2003) made no hydrological difference in the dry condition of the Lake Volta during the period that followed (2003–2006). Although the amplitude of Oti river discharge was more than 2000 m^3/s in 2004, the limited flows of the Volta river system in 2005 and 2006 created a water deficit condition that resulted in a long dry period in the basin.
(5) The Lake Volta shows relatively strong sensitivity and lag to rainfall conditions and incoming flows from the Volta river system in the basin spanning between less than one year and up to two years. Nonetheless, the wet conditions of 2003 in the basin as indicated in (4) above, is inconsistent with the clustering of dry conditions in the Lake during 2003–late 2007 period. Since mankind naturally responds to changes in climate, this may suggest a possible water conservation and management strategy by the Volta river basin authority, to cushion the impact of the extended dry periods of the previous years caused by the influence of natural climate variations, on the Lake's hydropower potential. In addition, a 4–5 year cycle between dry and wet periods, resulting from the impact of climate variability in the basin was noticed.
(6) As the reservoir system of the Lake Volta is naturally connected to the Volta river system, the effects of this change in flow regime of the Volta river system and rainfall is likely to impact negatively on the water resources of the basin, perhaps the beginning of the Lake's desiccation if the trends are not reversed. With the availability of consistent and up to date gauge measurements of the three rivers (White Volta, Black Volta, and Oti rivers), the probability of the Lake's desiccation and the impact of human interventions such as the development of small and medium scale reservoir systems in the basin can be quantified.

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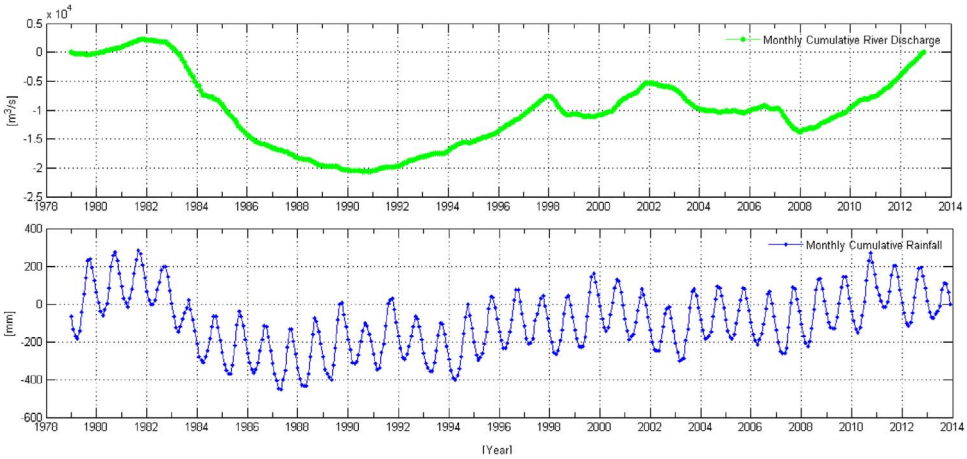

Fig. 16. Cumulative monthly rainfall and river discharge anomalies averaged over the Volta basin using the GPCC based precipitation and river discharge at Akosombo station, respectively. Top: Monthly cumulative river discharge anomaly over the basin during 1979–2012 period. Bottom: Monthly cumulative rainfall anomaly over the basin during 1979–2013 period.

Appendix A1. : Cumulative rainfall and river discharge departures

Appendix A2. : Recent trends in Lake Volta water levels (2002–2015)

The trends in Lake height variations (i.e., after removing the temporal mean of the period between 2002 and 2015) were further analysed using the method of least squares. The results indicate that 19.635 km^3 of water was gained between August 2007 and December 2010 while about 19.125 km^3 of water has been lost from January 2011 to date. Fig. 2 shows these periodic fluctuations and trends in lake level variations over Lake Volta during the GRACE period. The Lake Volta apparently shows a relatively strong rise and fall in lake heights during the 2007–2015 period compared to the 2002–late 2006 period. Specifically, between the periods 2002–2005 and 2005–2007, an estimated loss of 3.57 km^3 of water, compared with the gain of 0.51 km^3 of water for the periods between 2007–2011 and 2011–2015 largely indicates an approximate loss of 3.06 km^3 of water in the Lake for the entire period (i.e., 2002–2015). Since changes in surface water (i.e., Lakes, and reservoirs) in this region is largely driven by rainfall, the decline in the lake level is mostly attributed to the negative trends in precipitation (during the 2002–2014 period) around the vicinity of the Lake. The fall in the amplitude of the lake level in 2010/2011 may have been the fall-out of spilling the reservoir (Owusu and Waylen, 2013) due to heavy rainfall caused by a La-Niña event in 2010. Although this is rather implied than stated, the results of this study confirm that extreme rainfall in 2010 in the Volta basin is consistent with the strong rise of water level in the Lake Volta in the same year (Fig. 2). However, from a long term perspective of extreme rainfall conditions, emerging facts in a recent study by Ndehedehe et al. (2016c) indicate that Burkina Faso and the Lake Volta areas are predominantly drought zones with the possible influence of low frequency large scale oscillations. They specifically reported a hydrological drought condition at the Lake Volta area during the 2011–2013 period. This period falls within the most recent time window (2011–2015) of observed declines in lake level (Fig. 2). The results presented in Section 5.4 also confirm that besides 2003, 2007, and 2010, which were relatively wet years due to ENSO rainfall, the basin was generally characterised by precipitation deficits as extreme low standardised rainfall values were largely predominant.

The impact of rainfall on the Lake is well known. For instance, during the severe drought of 1983, the water level dropped drastically, reaching its lowest limit of 72 m (i.e., above mean sea level) in 1984 and rising again to maximum levels in 1989 and 1992, respectively during the periods of high rainfall (see, Zwieten et al., 2011). Moreover, hydrological drought years such as 1983, 1998, 2006 culminated in power rationing for the successive years of 1983/1984, 1999, and 2006/2007, respectively (see, Ndehedehe et al., 2016c; Bekoe and Logah, 2013). Tributaries such as the Black Volta and White Volta (see Fig. 1), which flows into Lake Volta are largely rain-fed. The Lake, which benefits from these tributaries swells and shrinks during the rainy and dry seasons, respectively. Furthermore, between 1966 and 2006, Zwieten et al. (2011) reported an average gradual decrease of 15 cm/yr in water levels. The observed decline of 2.25 $\pm$ 0.10 m/yr from January 2011 to date may impact negatively on the Lake as the lowest minimum water level of 2015 is approaching those of water deficit years of 2003 and early 2007 (Fig. 2). In addition to the influence of hydro-meteorological conditions, non-climatic factors such as the widespread construction of numerous hydraulic infrastructures (e.g., small-scale reservoirs and large scale irrigation systems) in Burkina Faso and Ghana for water mobilization to support agriculture in the basin, especially during the long dry season, have been reported (e.g., Amisigo et al., 2014). This and evaporation loss over the Lake may ultimately put the water resources of the lower Volta at risk.

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