Accepted Manuscript

Water storage changes and climate variability within the Nile Basin between 2002-2011

J.L. Awange, E. Forootan, M. Kuhn, J. Kusche, B. Heck

PII: S0309-1708(14)00127-4
DOI: http://dx.doi.org/10.1016/j.advwatres.2014.06.010
Reference: ADWR 2227

To appear in: Advances in Water Resources

Received Date: 4 December 2013
Revised Date: 9 June 2014
Accepted Date: 20 June 2014

Please cite this article as: Awange, J.L., Forootan, E., Kuhn, M., Kusche, J., Heck, B., Water storage changes and climate variability within the Nile Basin between 2002-2011, Advances in Water Resources (2014), doi: http://dx.doi.org/10.1016/j.advwatres.2014.06.010

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.
Water storage changes and climate variability within the Nile Basin between 2002-2011

J.L. Awange, E. Forootan, M. Kuhn, J. Kusche, B. Heck

Abstract

Understanding water storage changes within the Nile’s main sub-basins and the related impacts of climate variability is an essential step in managing its water resources. The Gravity Recovery And Climate Experiment (GRACE) satellite mission provides a unique opportunity to monitor changes in total water storage (TWS) of large river basins such as the Nile. Use of GRACE-TWS changes for monitoring the Nile is, however, difficult since stronger TWS signals over the Lake Victoria Basin (LVB) and the Red Sea obscure those from smaller sub-basins making their analysis difficult to undertake. To mitigate this problem, this study employed Independent Component Analysis (ICA) to extract statistically independent TWS patterns over the sub-basins from GRACE and the Global Land Data Assimilation System (GLDAS) model. Monthly precipitation from the Tropical Rainfall Measuring Mis-
sion (TRMM) over the entire Nile Basin are also analysed by ICA. Such extraction enables an in-depth analysis of water storage changes within each sub-basin and provides a tool for assessing the influence of anthropogenic as well as climate variability caused by large scale ocean-atmosphere interactions such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Our results indicate that LVB experienced effects of both anthropogenic and climate variability (i.e., a correlation of 0.56 between TWS changes and IOD at 95% confidence level) during the study period 2002-2011, with a sharp drop in rainfall between November-December 2010, the lowest during the entire study period, and coinciding with the drought that affected the Greater Horn of Africa. Ethiopian Highlands (EH) generally exhibited a declining trend in the annual rainfall over the study period, which worsened during 2007-2010, possibly contributing to the 2011 drought over GHA. A correlation of 0.56 was found between ENSO and TWS changes over EH indicating ENSO’s dominant influence. TWS changes over Bar-el-Ghazal experienced mixed increase-decrease, with ENSO being the dominant climate variability in the region during the study period. A remarkable signal is noticed over the Lake Nasser region indicating the possibility of the region losing water not only through evaporation, but also possibly through over extraction from wells in the Western Plateau (Nubian aquifer).

**Keywords:** Nile Basin, Lake Victoria, Ethiopian Highlands, Bar-El-Ghazal, GRACE- total water storage, climate variability
1. Introduction

The Nile River Basin is one of the largest basins in the world, with an area of about 3,400,000 km\(^2\) (almost one-tenth of Africa). It traverses about 6,500 km from the White Nile in the south to the Mediterranean Sea in the north as it winds its way across the boundaries of eleven countries supporting livelihoods of over 300 million people (Awange et al., 2013a). Because of this huge size of the Nile Basin, climate variability and change that is manifested locally or regionally may have regional and even international consequences through its effects on Nile river flows (Conway, 2005).

The Nile’s water resources have come under threat from both anthropogenic and natural factors (see, e.g., Hamouda et al., 2009). Indeed, that hydrological regimes respond to climate change and anthropogenic influences have been reported, e.g., in (Beyene et al., 2010), (Konar et al., 2013) and (Destouni et al., 2013). For the Nile River Basin, anthropogenic influences are attributed to increased human population that has put pressure on domestic water needs and hydroelectric power supply, all coupled with the need to sustain economic growth (e.g., Awange and Ong’ang’a, 2006; Awange et al., 2008, 2013a,b). Furthermore, not only are the demands on water increasing, but also the available water supplies appear to be decreasing, with environmental degradation of the upper Blue Nile catchment having increased throughout the 1980s (Whittington and McClelland, 1992). For example, due to the large and increased population pressure, insufficient agricultural production, a low number of developed energy sources, and drought episodes; Ethiopia, which contributes about 85% of the Nile’s annual flow (Sutcliffe and Parks, 1999), but has almost 94% of its popula-
tion depending on wood fuel, is planning major hydropower and irrigation development (Block et al., 2007; Tesemma et al., 2010; Tesfagiorgis et al., 2011; Berhane et al., 2013). In addition to irrigation and hydroelectric power, land degradation and changes in land cover in Ethiopia where forest lands are being converted to agricultural land are having impact on the Nile flow (see, e.g., Senay et al., 2009; Rientjes et al., 2011). Such measures are likely to impact on the downstream countries of Egypt and Sudan whose populations have been increasing, thus posing a challenge to water allocation (see Whittington and McClelland, 1992; Awange and Ong’ang’a, 2006; Awange et al., 2013a,b).

Natural factors have been the subject of numerous studies as shown in the works of Beyene et al. (2010), Conway (2005) and Yates (1998, and the references therein) who investigated the influence of the changing climate on the Nile waters; Ghoubachi (2010) and Sefelnasr (2007) who considered groundwater movement. For the Nile river discharge, for example, the influence of climate variability and change has been shown e.g., by Eltahir (1996) and Amarasekera et al. (1997) to account for 25% of natural variability in annual discharge. Knowledge of climate variability is essential not only for predicting its floods and droughts (Eltahir, 1996; Korecha and Barnston, 2007), but also for understanding of global atmospheric dynamics since streamflow is an index of precipitation integrated over large areas (Amarasekera et al., 1997).

To support the management of the Nile Basin’s water resources (e.g., supply, demand and sustainable use; Hanson et al., 2004), it is essential to understand the changes in its stored water (surface, groundwater, and
soil moisture) and their relation to climate variability such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Due to its large spatial extent, however, changes in Nile Basin’s stored water cannot be monitored using traditional methods (e.g., piezometric-based). This calls for satellite based methods of observation. One such satellite is the Gravity Recovery And Climate Experiment (GRACE) whose use offers a unique chance to monitor changes in the total water storage (TWS, i.e., an integral of surface, groundwater, and soil moisture storage) within the Nile Basin (see, e.g., Awange et al., 2008, 2013a,b; Becker et al., 2010; Bonsor et al., 2010; Senay et al., 2009; Swenson and Wahr, 2009; Longuevergne et al., 2012).

The main challenges in using GRACE-TWS changes over the Nile Basin is that on the one hand, the derived hydrological signals are dominated by stronger signals, e.g., those around the lakes such as Lakes Victoria and Tana (see, e.g., Awange et al., 2013b), as well as regions close to the Red Sea and the Mediterranean Sea (Aus der Beek et al., 2012). Computing basin average water variations, therefore, is normally influenced by dominant signals such as that of Lake Victoria Basin (LVB), while the relatively weaker signals from the other regions are masked making analysis of changes in TWS over such sub-basins difficult. On the other hand, Rodell and Famiglietti (2001) pointed to the limitation of GRACE products to study basins of less than 200,000 km². Since some of the Nile’s sub-basins (e.g., Lake Nasser region) have areas less than 200,000 km², thus, computing TWS changes of them is limited by the spatial resolution of GRACE (e.g., 400,000 km² in Swenson et al. (2003) and Tapley et al. (2004)). Previous analysis of the Nile
basin based on the GRACE satellite data have thus been unable to separate the signals into their respective sub-basins for the purpose of providing an in-depth analysis of spatial variations (see, e.g., Awange et al., 2013b).

To overcome these challenges, in the present study; (i) we apply a higher order statistical tool of Independent Component Analysis (ICA) (Spatial ICA in Forootan and Kusche, 2012, 2013) over the Nile Basin (between 10° S to 35° N and 25° E to 45° E) to separate GRACE-TWS changes between 2002 to 2011 into their spatially independent sources (i.e., sub-basins). This is then followed, in (ii), by an evaluation of the impacts of global climate change on the TWS within these sub-basins using global climate forcing by IOD and ENSO.

The remainder of the study is organized as follows; in the next section, the Nile Basin is briefly described. The methodology (data used in the study and the analysis approaches) are outlined in Section 3, and the results discussed in Section 4. Section 5 concludes the major findings.

2. The Nile Basin

The Nile Basin (Fig. 1) has two major tributaries, the White Nile and the Blue Nile, the latter being the main source of its water. The White Nile originates from the Great Lakes region of Eastern Africa, and flows northwards through Uganda and South Sudan. The Blue Nile on the other hand starts from Lake Tana in the Ethiopian Highlands (EH), flowing into Sudan from the southeast and meets the White Nile at Khartoum in Sudan. From there, the Nile passes through Egypt, which is mostly dry (i.e., 92%) and Sudan, and finally discharges into the Mediterranean Sea (see, e.g., Sahin
The four main areas of interest to our study, whose changes in TWS could be remotely sensed using GRACE satellite data due to their larger spatial coverage (i.e., over 200,000 km$^2$) are (see Fig. 1): (i) Lake Victoria Basin (LVB), which is the headwaters of the White Nile; (ii) the Bahr-el-Ghazal region (BEG), the main western tributary of the Nile, and the largest sub-basin. Its supply to the Sudd wetlands is however reported by Mohamed et al. (2006) to be negligible. Nonetheless, it is included in this study to assess the impacts of climate variability on its TWS changes. The Sudd wetlands (marshes) is the region between Mongalla and Malakal, which consists of marshes and lagoons, and is believed to be where most of the White Nile’s water is lost due to evaporation (Yates, 1998); (iii) the Ethiopian Highlands (EH), and the headwaters of the Blue Nile; and (iv) the Egyptian desert region consisting of Lake Nasser, where significant amounts of water are lost due to evaporation (see details of regions in Conway and Hulme, 1993). The characteristics of these regions are summarized in Table (1).

FIGURE 1

3. Data and Methodology

3.1. Data

The data used in this study consisted of remotely sensed GRACE-TWS changes from 2002 to 2011, Tropical Rainfall Measuring Mission (TRMM)-derived precipitation, and water storage data from Global Land Data Assimilation System (GLDAS) hydrological model over the same period.
3.1.1. Gravity Recovery And Climate Experiment (GRACE)

GRACE, a joint US-German satellite project launched in March 2002, detects spatio-temporal variations of the Earth’s gravity field (Tapley et al., 2004). There are a number of institutions delivering GRACE products, each applying their own processing methodologies and, often, different background models. In this work, we examined gravity field time series provided by the German GeoForschungsZentrum (GFZ), Potsdam (Flechtner, 2007). GFZ’s release (RLO4) gravity field solutions are provided at monthly resolutions and consist of a set of fully normalized spherical harmonic coefficients of the geopotential, up to degree and order 120. These coefficients are contaminated by correlated errors, manifesting as stripes in the spatial domain. These striping and high-frequency effects potentially mask hydrological signals, making their detection extremely difficult (e.g., Kusche, 2007; Awange et al., 2009). In this regard, the GFZ solutions were smoothed using the DDK2 de-correlation filter (Kusche et al., 2009). Filtered solutions can also be downloaded from the official website of the International Center for Global Gravity Field Models. We chose RLO4 version and the DDK2 filter to be consistent with previous studies, e.g., that of Awange et al. (2013a,b). In addition, we neglected any estimates for the degree 1 coefficients due to its small contribution to water storage estimation of the basin.

In order to derive the TWS changes, residual gravity field solutions taken with respect to 9 years (assumed static) average were derived. The resulting residual geopotential coefficients were then transformed into monthly TWS

\(^2\text{(http://icgem.gfz-potsdam.de/ICGEM/TimeSeries.html)}\)
changes using Wahr et al. (1998)’s approach. Besides the total signals of
the respective sub-basins, this study explored the possibility of analyzing the
residual signals once the dominant signals of Lake Victoria, Lake Tana and
the Red Sea were removed. To remove the lakes’ signals from GRACE-TWS
changes, we followed the approach in Swenson and Wahr (2002). The surface
height of each lake was assumed to be changing homogeneously. For each
lake, a global grid was defined by a function $f$, where its surface was given a
value 1 and 0 over the rest of the globe (i.e., equivalent to 1 mm Equivalent
Water Thickness (EWT) over the lake and zero over the rest of the globe).
The lake grid function $f$ is then defined over a sphere (with radius $R$) as

$$f(\lambda, \theta) = \frac{1}{4\pi} \sum_{n=1}^{120} \sum_{m=0}^{n} \bar{P}_{nm}(\cos \theta) \left[ c_{nm}^{f} \cos(m \lambda) + s_{nm}^{f} \sin(m \lambda) \right], \tag{1}$$

where $\bar{P}_{nm}$ are the normalized associated Legendre functions, $\lambda$ and $\theta$ represent the geocentric positional vector in spherical coordinates. Since the
function $f$ was known by definition, the spectral values of $c_{nm}^{f}$ and $s_{nm}^{f}$
in Eq. 1 were derived by integration (Wang et al., 2006). The estimated spherical harmonic coefficients ($c_{nm}^{f}$ and $s_{nm}^{f}$) were then filtered using the DDK2 (Kusche et al., 2009). Finally, each field was scaled using the sea surface heights (SSH) time-series (in mm) derived from Jason 1 and 2 satellite altimetry data (Crétaux et al., 2011). The altimetry data were downloaded from the LEGOS website (http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/). This procedure transferred SSH changes of the desired lake to what GRACE could see as a whole. As an example, in Fig. 2, the satellite altimetry-derived EWT changes and GRACE-TWS
time series corresponding to Lake Victoria over the period 2002 to 2011 are shown.

FIGURE 2

3.1.2. Tropical Rainfall Measuring Mission (TRMM)

TRMM, a joint Japanese/USA satellite mission (see Kummerow et al., 1998), launched in 1997 provides measurements of the spatial and temporal variation of the tropical rainfall in the latitude range $\pm 35^\circ$ over inaccessible areas such as the oceans and unsampled terrains. TRMM data has been validated and employed in a number of studies of African precipitation, where they have been found to be adequate (see, e.g., Nicholson et al., 2003; Awange et al., 2013a,b). For example, Awange et al. (2008, 2013a,b) applied TRMM to study the Nile Basin while Naumann et al. (2012) found TRMM data to be reliable enough to be used for drought monitoring over Africa. The use of TRMM satellite data for this study, therefore, is informed by the works of Awange et al. (2013a,b) and the references therein. The present work utilized the DDK2-filtered TRMM 3B43 records for the period 2002 to May 2011 for comparisons with GRACE-TWS changes.

3.1.3. Global Land Data Assimilation System (GLDAS)

GLDAS hydrological model integrates a huge quantity of observation based data and modeling concepts (see, e.g., Rodell et al., 2004) including a global Land Information System (LIS) at a spatial resolutions $(0.25^\circ \times 0.25^\circ)$ (Kumar et al., 2006). The monthly GLDAS data set is distributed in two parts: (i) the energy budget (EB); and (ii) the water budget (WB). To
assess the water storage variations within the Nile Basin and their compar-
isons with GRACE-TWS changes, we used monthly WB data (including soil
moisture, snow and water canopy storages) covering the period from Au-
gust 2002 to October 2010\(^2\). The GLDAS data was also filtered using the
same DDK2 filter used for smoothing GRACE-TWS changes to have similar
spectral structure.

3.1.4. El Niño and Southern Oscillation (ENSO)

El Niño/Southern Oscillation (ENSO) is a large scale climate variability
that influences the global atmospheric circulation and its impacts on regional
climates depend on the region and season, and the strength and spatial dis-
tribution of the phenomenon (Clark et al., 2003; Colberg and Reason,
2004). ENSO has a strong influence on trade winds and climate of the East
African region, and has been observed to weaken the Hadley circulation (Col-
berg and Reason, 2004). It has significant influence on rainfall over Eastern
Africa (Indeje et al., 2000; Korecha and Barnston, 2007; Awange et al.,
2013a,b). The warm/cold (El Niño/ La Niña) phase of ENSO is associated
with enhanced/depressed seasonal rainfall over various parts of the region
especially during the October-December (OND) rainfall season (Indeje et al.
2000; Omondi et al., 2012, 2013a,b; Taylor et al., 2012).

The Southern Oscillation (SO) is measured using Southern Oscillation
Index (SOI) (Hastenrath et al., 1993). High SO phase is associated with high
and low pressure over the western and eastern Pacific Ocean, respectively
(Hastenrath et al., 1993), resulting in enhanced westerly and cooling over the

\(^{2}\)http://grace.jpl.nasa.gov/data/gldas/
western parts of the ocean. The low phase has the opposite effect of enhancing rainfall over the western Indian Ocean and East Africa (Hastenrath et al., 1993). The low-level circulation pattern associated with the above-normal rainfall over the region is dominated by easterly inflow from the Indian Ocean and westerly inflow from the Congo tropical rain forest into the positive rainfall region (Anyah and Semazzi, 2006). This study used monthly SOI provided by the Australian Bureau of Meteorology covering the period from 2002 to 2011\(^3\).

3.1.5. Indian Ocean Dipole (IOD)

The Indian Ocean Dipole (IOD) and the related Indian Ocean Zonal Mode (IOZM) is reflected, e.g., in the sea surface temperature (SST) data over the Indian ocean. IOD has been observed to have significant influence on rainfall over the East African sub-regions and other areas neighbouring the Indian Ocean see, e.g., Behera et al. (2005); Black et al. (2003); Clark et al. (2003); Taylor et al. (2012) and Awange et al. (2013a). IOD is caused by air-sea interactions in the tropical Indian Ocean leading to the warming/cooling of western/eastern tropical Indian Ocean during the positive/negative phases resulting into the reversal of SST gradients and changes in the zonal wind currents (Saji and Yamagata, 2003a,b).

The warm/cool western/eastern Indian Ocean is associated with enhanced/deficient OND seasonal rainfall over the sub-region (Saji et al., 1999; Behera et al., 2005; Black et al., 2003; Clark et al., 2003; Saji and Yamagata, 2003a,b) resulting from the anomalous changes in Walker circulation that

\(^3\)(http://www.bom.gov.au/climate/enso/)
lead to anomalous moisture transport and convergence (Behera et al., 2005). The influence of the IOD on rainfall over the sub-region is much higher than that associated with ENSO (Behera et al., 2005), and is strongest during the OND rainfall season. However, the co-occurred ENSO and IOD events are stronger than those that occur independently (Saji and Yamagata, 2003a,b; Song et al., 2007; Awange et al., 2013a). The Dipole Mode Index (DMI) is the gradient of the IOD event, which is usually used as a measure of the IOD influence of climate variability. In this study, we used DMI time series provided by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) covering the period from 2002 to September 2010.

3.2. Methodology

3.2.1. Extracting Independent Patterns

At regional scale, temporal changes in total water storage (TWS), measured by GRACE is related to precipitation $P$ through the water budget equation

$$\frac{d(TWS(t))}{dt} = P(t) - E(t) - R(t),$$

(Becker et al., 2010; Rodell et al., 2004), where $P$ is precipitation, $E$ for evapotranspiration and $R$ is river discharge measured in time ($t$). In order to evaluate TWS changes obtained by GRACE, this study explores the relationship between GRACE-TWS changes and TRMM precipitation product $P$ over the Nile Basin. Precipitation is used here based on the fact that

\[\text{(http://www.jamstec.go.jp)}\]
previous studies have shown its capability to detect and monitor land hydro-
logical changes obtained from time-variable gravity observations (see, e.g.,
Rieser et al., 2010; Awange et al., 2011; Fleming et al., 2012). When
comparing TRMM-rainfall with GRACE-TWS changes, however, it should
be kept in mind that they cannot be compared on a one-to-one basis since
GRACE observes the total mass changes that arises from all components of
the hydrological cycle, and not just precipitation. Nonetheless, precipitation
plays an important role in the terrestrial water balance, being the main re-
plenishment source of large-scale TWS changes. Analysis of the contribution
of E and R over the basin are outside the scope of the present study and will
be treated in future contributions.

In order to assess the water storage changes within the Nile Basin, the
Spatial Independent Component Analysis (Spatial ICA) approach (see, Fo-
rootan and Kusche, 2012; Forootan et al., 2012) was used to extract the
 spatially independent signals within the Nile Basin boundary, selected to ex-
tend from 25°E < λ < 45°E and 5°S < ϕ < 35°N, including areas that do not
actually belong to the Basin, such as the Red Sea (Fig. 1). For instance,
assuming that time series of TWS fields, after removing their temporal mean,
are stored in a matrix $X_{TWS} = X_{TWS}(t, s)$, where $t$ is the time, and $s$ stands
for spatial coordinate (grid points). Applying Spatial ICA, $X_{TWS}$ can be
decomposed into spatial and temporal components as

$$X_{TWS} = A_j S_j,$$

where $A_j (t \times j)$ stores the $j$ dominant unit-less temporally evolution of
TWS changes in its columns, and the rows of $S_j (j \times s)$ represent their

14
corresponding statistically independent spatial maps. Each temporal pattern (a column of $A_j$) along with its corresponding spatial pattern (a row of $S_j$) provides an independent mode of variability (Forootan and Kusche, 2012, 2013). The use of the Spatial ICA method, which is simply called ICA from now on, is advantageous in two respects: first, it localizes the signals and isolates those outside the basin; and second, it provides statistically independent components, which enhance the interpretation of the results.

To understand the advantages of using ICA in localizing TWS changes over the Nile Basin, let us use a simple illustration of Fig. 3 based on simulated data. Let us assume that the water storage changes of the Nile Basin consists of changes in lake water storage, soil moisture, and sea storage. We demonstrate the power of the ICA (Forootan and Kusche, 2012) in a two-step approach (see, also Forootan et al. (2012) for a simulation example on Australia). In the first step, we simulate the combined lake water storage, soil moisture, and sea storage over the Nile Basin and in the second step, we apply the ICA approach to localize them into their respective separate components. To achieve the first step, altimetry data from the LEGOS website (Crétaux et al., 2011) are used to introduce the Lake water storage changes, which are then converted to EWT using the approach discussed in section 3.1.1. The same approach is used to covert the level variations of the Red Sea\(^5\) into EWT changes, while the soil moisture are introduced from the GLDAS model (section 3.1.3). From the first step, Fig. 3(top-A) shows the introduced signals of lakes, Fig. 3(top-B) corresponds to soil moisture changes, and Fig.

\(^5\)(from http://coastwatch.pfeg.noaa.gov)
3(top-C) represents the introduced signals over the sea. Combined, Figs. 3(top-A, B, and C) leads to Fig. 3(top-D) that contains a summation of all the signals. As can be seen from Fig. 3(top-D), the composition of the mixed signals make it hard to interpret thereby necessitating the need for ICA method to separate them and make them interpretable. Now, applying the ICA method to the combined introduced patterns of Fig. 3(top-D) in order to separate the signals to their respective sources, the results of Fig. 3(bottom) show that the introduced water storage changes over the Red Sea and Lake Nasser having been separated as the first independent mode (IC1). Soil moisture pattern has been separated as the second independent mode (IC2), and finally, water storage changes of Lake Vitoria are localized in the third independent mode (IC3). The successful performance of ICA in localizing the simulated water storage changes motivated its application to real GRACE-TWS data over the Nile Basin. For more discussion on the ICA-method, its performance on decomposing GRACE-derived TWS fields, as well as its comparison with the second order statistical method of Principal Component Analysis (PCA), we refer to Forootan and Kusche (2012) and Forootan et al. (2012, 2014). The main independent patterns of GRACE/GLDAS-derived TWS changes are therefore compared to those of TRMM rainfall (considered as the main input of TWS changes over the Nile Basin).

FIGURE 3

16
3.2.2. Correlation Analysis

In order to study the relations between the patterns of TWS changes within different Nile sub-basins and climate teleconnections (i.e., ENSO and IOD), correlation analysis between ICs of GRACE-TWS changes and those of ENSO and IOD indices was performed. To this end, first, the independent components (ICs) of GRACE-TWS changes and indices were smoothed using a 12-month moving average filter and interpolated to a regular monthly time steps covering the period from October 2002 to May 2011. The temporal filter was applied to decrease the effects of strong inter-annual variability on the computed correlations (see e.g., Forootan et al., 2012; García-García et al., 2011). The correlation analysis are then performed at 95% level of confidence over the complete period in order to study the long-term impacts of climate variability on TWS changes of the Nile’s sub-basins.

4. Results

4.1. Comparisons of GRACE-TWS, GLDAS-TWS, and TRMM-Rainfall Changes

Before undertaking a detailed analysis of the water storage changes within each sub-basin, overall comparison of the similarities and differences between GRACE, TRMM, and GLADS was performed by applying correlation analyses between data sets at 95% confidence level, where significant bounds based on an asymptotic normal distribution with the variance of 1/(n-3) were set (Lehmann, and D’Abrera, 1998). Those correlations that were smaller than the estimated bounds were set to zero. Figure 4 presents the spatial variation of the correlations, indicating the high rainfall impact on TWS changes over the tropical regions, Ber-el-Ghazal (BEG), and parts of Ethiopian Highlands.
Lower correlations in other regions might reflect a higher influence of unaccounted evaporation and runoff.

Implementing ICA on GRACE-TWS changes produced 4 significant spatially independent components over the study region corresponding to 92% of the cumulative total variance of TWS changes (see Fig 5). In comparison to GRACE, GLDAS and TRMM data sets each produced 3 significant modes of ICs, which corresponded to 86% and 91% of total variance respectively (see Figs A1 and A2 in the Appendix). The variances suggest that the presented independent modes extract the dominant large scale variability of TWS (particularly from GRACE compared to GLDAS) and rainfall changes within the basin and thus are representative enough to be individually subjected to further analysis and interpretations. For all the ICA results presented here, the independent modes are ordered with respect to the variance they represent. The presented spatial maps are statistically independent with respect to each other and are scaled by the standard deviation of their corresponding temporal ICs to represent anomaly maps in mm, while the temporal ICs are divided by their standard deviations to be unitless.

Figure 5 shows the first independent mode (spatial and temporal patterns of IC1) of GRACE to be localized over the BEG region (dominated by an annual signals), the second independent mode (IC2) is localized over the EH, the third independent mode (IC3) over LVB, and finally the fourth independent mode (IC4) is found to be over the Red Sea and the northern parts of the basin. In comparison, the spatial pattern of Figure A1 (Appendix) of GLDAS captures a similar pattern over the BEG, and the anomalies over the northeast part of the LVB. It, however, shows a weaker signal over EH.
Figure A2 (Appendix) shows the ICA results of rainfall variability over the basin, where the rainfall signal over LVB in the first mode (IC1) and EH in the second mode (IC2). It does not show any rainfall related fluctuations over the Red Sea. Given the high percentage of variability captured, i.e., 92%, and its capability to capture signals from various regions, the proposed use of GRACE-based TWS changes of the Nile sub-basins are adequate for further analysis. The TWS from GLDAS and the TRMM-derived rainfall changes will thus not be treated further.

With the removal of Lake Victoria’s signal using the procedure discussed in section (3.2), the TWS from GRACE data did not change for BEG but is concentrated more over the catchments for LVB and EH (Fig. 6). For the Nasser region, the removal of the Red Sea and the Lake Nasser signal allowed the possible impact of ground water extraction in the the Western Plateau (Nubian aquifer; e.g., Sultan et al., 2012) to be more visible (e.g., Fig. 7). The results of correlations between TWS changes in different sub-basins and the climate variability of ENSO and IOD are summarized in Table 2.

4.2. Analysis of stored water and climate variability over the sub-basins

4.2.1. Bahr-el-Ghazal region (BEG)

Bahr-el-Ghazal (BEG) sub-basin consists of a number of rivers that originate from the Congo-Nile River divide and is made up of a large area of
very low slope such that nearly all the basin runoff and precipitation is evaporated or leaked into swamps (i.e., about 96% is lost), with only about 0.5 km³ leaving the basin annually (Conway and Hulme, 1993). From the estimated GRACE-TWS patterns in Fig. (5, IC1), increased water storage for this region in the period between 2002 to 2003 at a rate of 64.4 mm/year was noticed. This could be explained by the increase in total annual rainfall between 2002-2004 (see, e.g., Fig. A2, IC3, in the Appendix). Between 2003 and 2006, GRACE-TWS changes showed a reduction at a rate of 29.2 mm/year, again, in line with the noticeable reduction in total annual rainfall from TRMM (see Fig. A2, IC3, in the Appendix). From 2006 to 2007, the stored water increased at a rate of 74.9 mm/year although the TRMM rainfall over this period does not show significant increase. This could imply reduced evaporation since the correlation between GRACE-TWS changes and the TRMM-rainfall over BEG gives a phase lag of 1-month at a maximum correlation of 0.53.

The ICA-derived TRMM-rainfall pattern in BEG region showed similarities to that of EH (Fig. A2, IC3, in the Appendix) but with higher amplitudes during 2002-2004 period. The BEG sub-basin experienced a reduction in total annual rainfall from 2003 to 2007, i.e., an increase in 2008, then a decrease between 2009 and 2010 before starting to increase again (Fig. A2, IC3, in Appendix). The drop seen in Fig. (A2, IC3, in Appendix) supports the deductions of Di Baldassarre et al. (2011) stating that the three sub-basins; Bahr-el-Ghazal, Sobat and Central Sudan within the Nile Basin recorded significant drops in annual precipitation.

For the study period 2002 to 2011, we found an insignificant correla-
tion (0.18) between GRACE-TWS changes and IOD, and a strong positive correlation (0.71) between GRACE-TWS changes and ENSO (Table 2). These correlations suggest that ENSO is the dominant climate variability associated with TWS changes over the BEG sub-basin.

4.2.2. The Ethiopian Highlands (EH); The Blue Nile

Analysing GRACE-TWS changes over Ethiopian Highlands (EH) (Fig. 5, IC2) showed a decline at a rate of 18.4 mm/year between 2002-2006. This decline can be explained by the temporal curve of the rainfall (Fig. A2, IC2 in the Appendix), which shows a decline in annual rainfall for the period 2002 to the end of 2005. A similar decline was noted by Di Baldassarre et al. (2011) who studied the changes in land cover, rainfall, and streamflow of Gilgel Abbay catchment, the largest contributor to the inflow of Lake Tana (the source of the upper Blue Nile; e.g., Conway and Hulme (1993)), and found that changes in streamflow records for the period 2001-2005 could have been attributed to changes in land cover, and changes in the annual and seasonal distribution of rainfall. Between 2006-2007, GRACE-TWS changes showed an increase in stored water at a rate of 44.3 mm/year. This could be attributed to the more than normal rainfall during the peak season of July-August as indicated by the amplitude of TRMM rainfall for 2006-2007 in Fig. A2, IC2 (in the Appendix). Jury (2011) found high peaks of the 2006-2007 in Ethiopian floods, which occurred in the periods 23-28 July 2006 and 26-31 July 2007. The floods are attributed to rainfall associated with sea surface temperature anomalies over the western Indian Ocean (Jury, 2011).

ENSO is reported to have a reverse effect, i.e., deficient rainfall tends to occur during ENSO summers (e.g., Eltahir, 1996; Korecha and Barn-
ston , 2007). Thus the Blue Nile sub-basin experienced drought episodes
during ENSO warmer phases and enhanced rains during the ENSO cooler
phases. Since 2006-2007 was an ENSO year in East Africa, one would ex-
spect less rainfall within the Blue Nile. The increase in the rainfall seen in
TRMM’s temporal graph (Fig. A2, IC2, in the Appendix), therefore, could
be attributed to other factors such as the influence of IOD, given that this
study obtained a correlation of 0.61 between the TRMM rainfall and IOD
as opposed to 0.43 between TRMM and ENSO (results not shown). Indeed,
that IOD exerts influence over the same region is reported by Korecha and
Barnston (2007) to have occurred during the 1997 ENSO year. From 2007
to 2011 (Fig. 5, IC2), the temporal curves of GRACE indicate reductions
in TWS at a rate of 12.8 mm/year. This is due to a general reduction in
the total annual rainfall as seen from the TRMM in Fig. A2, IC2 (in the
Appendix).

EH receives most of its rains in the period JJAS, which accounts for 50%
to 80% of annual rainfall totals over the region, contributing to high agricul-
tural productivity and major water reservoirs (e.g., Korecha and Barnston ,
2007). The peak of the JJAS rainfall occurs between July and August while
the dry season takes place between October to May (e.g., Rientjes et al. ,
2011). The temporal results of TRMM rainfall for EH in Fig. A2, IC2 (in
the Appendix) show a general decline in the total annual rainfall over the
study period, with the period 2007-2010 being mostly affected. This could
be due to the reduced amount the maximum rainfall recorded during the
long high rainfall (JJAS) season, and could possibly explain the cause of the
drought that faced the Greater Horn of Africa (GHA) over that period. Di
Baldassarre et al. (2011) points to a decreasing seasonality in some key watersheds of the upper Nile in Ethiopia such as the southern Blue Nile. For the Blue Nile sub-basin, Amarasekera et al. (1997) found a significant negative correlation between discharge and ENSO. For TWS, likewise, the positive correlations between ENSO and GRACE, i.e., (0.54 in Table 2), support the fact that ENSO is the dominant climate variability. However, the influence of IOD on TWS is also noticeable, i.e., 0.31 with respect to GRACE. With the removal of Lake Tana’s signal, there is a shift in the GRACE signals (Fig. 6A) further towards the highlands.

The magnitude of the rate of change in stored water remains relatively the same (i.e., 44.3 mm/year) for the period April 2006 to December 2007 even after removing the signals of Lake Tana. For the period August 2002 to April 2006 and December 2007 to March 2012, the rate of decline in stored water within the highland is of the same order of magnitude as before the removal of Lake Tana’s signal (e.g., 18.4 mm/year and 12.8 mm/year respectively). This further confirms the well known fact that the contribution of the Blue Nile’s waters comes mainly from these highlands. This fact is supported by the computed correlations to climate variability, which increases slightly for IOD (0.47) but remains the same for ENSO (0.59, e.g., Table 2). The slight increase in correlation with IOD following the removal of Lake Tana’s signals signifies that the stored water within the lake Tana dominates the entire sub-basin.

4.2.3. Lake Victoria Basin (LVB); The White Nile

Fig. 5 (spatial and temporal patterns of the third mode, IC3) presents the results of changes in water storage over LVB. From the spatial maps,
GRACE-TWS changes indicate dominant anomalies over the western part of the Lake (Fig. 5, IC3). Looking at the spatial pattern of IC3 (Fig. 5) together with its associated temporal pattern, the most significant drop in water level within the basin occurred between October 2003 to the March 2006, consistent with the findings of Awange et al. (2008), Swenson and Wahr (2009) and Becker et al. (2010). The rate of fall in water computed for LVB within this period, for the data within our selected study area, was 84.5 mm/year. From March 2006 to May 2007, however, the TWS within LVB increased at a rate of 145.2 mm/year due to the ENSO related rainfall (i.e., Fig. A2, IC1 in the appendix indicates an increase in the amplitude of rainfall between 2006-2007). Becker et al. (2010) who used the Global Precipitation Climatology Project (GPCP) observed an increase in precipitation from the end of 2005 to the beginning of 2007. For the study period, the correlations between GRACE-TWS changes and IOD was 0.48 and 0.56 with ENSO suggesting that both IOD and ENSO influence TWS changes in LVB.

The evidence that rainfall is influenced by the ENSO is supported by the fact that a positive correlation of 0.72 is obtained between GRACE-TWS changes and ENSO over the period 2007-2011 (see Table 1) consistent with Becker et al. (2010) who obtained a positive correlation value of 0.8 between TWS of GRACE and those of GPCP for the period 2005-2008. The period between May 2007 and August 2009 saw a drop in the TWS of LVB at a rate of 25.8 mm/year before it rose again at a rate of 49.8 mm/year due to increased rainfall from 2009 (see IC1 of Fig. A2 in the Appendix).

As for the rainfall, the first independent mode (see, IC1 in Fig. A2 in
the appendix) indicate a reduction between 2004 and about mid 2006, which coincides with the drought that was experienced in the region (see, e.g., Becker et al., 2010). During the period 2006-2007, there was ENSO and IOD induced increase in rainfall but the decline commenced after 2007 with the lowest level reached at the start of 2011. This was the lowest level of rainfall attained during the entire study period of 2002-2011, and was mainly due to a failed season and drought that affected the Greater Horn of Africa that started around that period (Omondi et al., 2013a). We found that TRMM-rainfall changes supersede GRACE-TWS changes with a phase lag of 1 month with a maximum lag correlation of 0.52.

In Fig. 6B, the contribution of Lake Victoria’s signal is removed as discussed in section 3.2 in order to study the residual catchment’s stored water signals. With the removal of the signals, the remaining catchment’s signal in Fig. 6B indicate a similar behaviour for the period 2003-2004 and 2006-2007 before the signal was removed. The dominant GRACE signals appears on the western side of the catchment in line with TRMM rainfall data (IC1 in Fig. A2 in the Appendix), indicating the rainfall to be more towards the western side of the catchment. During the long rainy season of March-April-May (MAM), the western side of Lake Victoria receives more rainfall than the eastern part thus recharging the stored water causing an increase (cf. Awange et al., 2013a). Regarding the influence of climate variability on the catchment’s stored water between 2002-2011, there is a decrease in correlations between ENSO (0.46) and GRACE-TWS changes after the removal of the Lake’s signals (see Table 2). This could be attributed to the influence of climate variability on the rainfall that falls on the western side of Lake Vic-
toria, which provides most of the source of the stored water. In interpreting the results of the removed Lake’s signals, however, it should be pointed out that remnant residual Lake’s signals (e.g., Fig. 6B) also contribute to the correlation, hence any conclusion needs to be taken with care.

In general, for LVB, over the study period of 2002 to 2011, and within our selected boundary, the ICA analysis of GRACE-TWS changes showed that the changes in LVB’s TWS experienced periods of significant decrease (e.g., 2002-2006) and significant increase (e.g., 2006-2007). Both anthropogenic and climate variability could have played significant contributions to these occurrences, i.e., with the 2003-2006 decrease hugely associated with the expansion of the Owen Falls dam (e.g., Awange et al. (2008) and Swenson and Wahr (2009) while the 2005-2007 increase is associated with climate variability (ENSO and IOD) as seen by comparing indices with the ICs of GRACE-TWS changes. For the catchment’s stored water, a similar deduction could be made, i.e., the expansion of the Owen Falls/Nalubale dam could have affected not only the Lake but also its catchment.

In contrast to the White Nile’s water discharge from LVB, where the influence of ENSO climate variability has been shown to be weak (i.e., a weak negative association with ENSO; Eltahir (1996) and Amarasekera et al. (1997)), the influence of climate variability on TWS changes within the basin is strong (see Table 2). LVB’s general TWS trend showed a decline even after the 2007 ENSO that saw a rise in its TWS. This general decline impacts upon the entire Nile Basin as evident from the water levels of Lake Nasser (e.g., as reported also in Becker et al. (2010) and Crétaux et al. (2011)), which follows the pattern of Lake Victoria even though the Blue
Nile contributes most of the Nile’s waters serving Egypt and Sudan.

4.2.4. Lake Nasser region

For this region, the ICA-derived GRACE-TWS anomalies were localized to the northwest-southeast direction of the Red Sea (Fig. 5, IC4). This signal could be largely attributed to the water storage changes within the Red Sea and Lake Nasser and thus needs to be removed. The use of altimetry data to remove the dominant GRACE signals from the Red Sea is supported by a correlation of 0.71 between GRACE-TWS changes and the altimetry data for the Red Sea. Altimetry observations provided by NOAA ERDDAP (the Environmental Research Division’s Data Access Program program)\(^6\) over the Red Sea were converted to EWT changes (see the conversion procedure in section 3.1.1) and scaled by its variance to unit-variance (i.e., IC4 of GRACE, c.f., Fig. 5D). Some differences in amplitude were detected (compare the amplitudes of red and blue in Fig. 7C) mainly in 2004, 2005, and after 2008. The residual of GRACE-TWS changes minus Red Sea-EWT is shown in black. Lake Nasser’s altimetry are also converted into EWT time series (same procedure as for the Red Sea), the results of which are shown in cyan. As can be seen, after 2008, the EWT changes corresponding to Lake Nasser is very similar to the residuals (the black line; Fig. 7C).

After the removal of the dominant signal of the Red Sea, the resulting signal (c.f. Fig. 7A) indicates a decline in stored water in the Western Plateau within the Nubian Aquifer covering Lake Nasser at a rate of 2.6 mm/year (cf. -3.5 mm/year for the period April 2002 to November 2010

\(^6\)http://coastwatch.pfeg.noaa.gov
in Sultan et al. (2012). The loss of water in this region is attributed by Sultan et al. (2012) to the fact that most of the water is extracted from the Nubian Aquifer and used for agricultural purposes that largely occur throughout the winter season, and also due to the fact that the Uwei-Aswan uplift prevents recharge of ground water flowing from the South to the North. To strengthen this argument is the fact that expansions of some large irrigation schemes such as East Uweinat project has seen heavy utilization of groundwater. In the East Uweinat project, for example, the lands reclaimed amounted to 1,200 ha in 1992 and 4,200 ha in 2003, with the target of reclaiming a total of 75,000 ha by 2022, all of which will be irrigated using groundwater (see, e.g., Salem and Pallas, 2002; Salem, 2007).

No dominant independent pattern was observed from TRMM and GLDAS data over the region surrounding lake Nasser, indicating that precipitation and soil moisture changes during the study period 2002-2011 was not the source of the observed TWS changes (see Fig. 7A). This supports the fact that the stored water within the Lake Nasser basin originates from the other Nile sub-basins. Weaker negative correlations were observed between GRACE and ENSO (-0.10) for the study period. During the same period, the correlation between GRACE and IOD was 0.13. Without the Red sea and Lake Tana’s signals, correlations between IOD and ENSO on the one hand and GRACE-TWS changes on the other hand were respectively 0.33 and 0.30, thus following closely to the LVB pattern (i.e., 0.48 and 0.46 for IOD and ENSO, respectively, for the same).

FIGURE 7
5. Conclusion

Using the ICA method (Spatial ICA in Forootan and Kusche, 2012; Forootan et al., 2012), we were able to extract independent water storage patterns of the Nile sub-basins and relate them to climate variability over the study period 2002-2011. For the individual sub-basins, the study found that:

1. The stored water within LVB could have been influenced both by anthropogenic as well as climate variability (ENSO and IOD). The removal of the dominant Lake Victoria signal shows the western side of Lake Victoria having increased TWS, a possible consequence of the long rains of the MAM season that pounds the western side of the lake more.

2. Ethiopian Highlands (EH) experienced a general reduction in rainfall as seen from the TRMM data over the study period from 2002 to the end of 2010, with the period between 2005-2010 recording low rainfall during the long rainy season of JJAS and low total annual rainfall, a possible explanation for the 2011 drought that hit the Greater Horn of Africa (GHA). This reduction in rainfall impacts on TWS changes over the GHA as seen from GRACE outputs (see also Omondi et al., 2013a).

3. Bar-el-Ghazal region showed a mixed increase/decrease in the stored water associated with increase/decrease in rainfall at different times of
the study period. The dominant climate variability in the region was found to be ENSO.

4. For the Lake Nasser region, it is clear that the dominant EWT changes of the Red Sea obscure the real impact of over extraction of water in the Nubian aquifer region for irrigation purposes (e.g., Sultan et al., 2012). The situation is not helped much by the fact that there could be insufficient recharge from the south-north flow of the groundwater due to the presence of the Uweinat-Aswan uplift.

5. In general, for almost all the sub-basins, the dominant climate variability on GRACE-TWS changes was the ENSO, with the exception of LVB and EH where the influence of IOD on GRACE-TWS changes was noticeable.
Acknowledgments J.L. Awange acknowledges the financial support of the Alexander von Humboldt Foundation (Ludwig Leichhardt’s Memorial Fellowship), The Institute for Geoscience Research (TIGeR), and a Curtin Research Fellowship that supported his stay in Karlsruhe (Germany) and Perth (Australia), the period during which parts of this study was undertaken. He is grateful for the warm welcome and the conducive working atmosphere provided by his host Prof. Heck at the Geodetic Institute, Karlsruhe Institute of Technology (KIT). E. Forootan and J. Kusche are grateful for the financial support by the German Research Foundation (DFG) under the project BAYESG. The authors are grateful to the GRACE-GFZ, GLDAS, TRMM, altimetry data, and climate indices used in this study. We also thank A. Ahunegnaw for Fig. 2, and J. Boy, M. Rodell, M. Sultan, and S. Swenson for their valuable comments on the manuscript during the AGU2011 Chapman Conference on Remote Sensing of Terrestrial Waters in Hawaii, USA. This work is a TIGeR publication (no. 568).
References


32


34


gauge data over Australia. Australian meteorological and oceanographic
Journal, 63, 421-426.


Ghoubachi, S.Y. (2010). Impact of Lake Nasser on the groundwater of the Nubia sandstone aquifer system in Tushka area, south west-


Sefelnasr A.M. (2007). Development of groundwater flow model for water resources management in the development areas of the western desert, Egypt. Dissertation, Faculty of Natural Sciences III of the Martin Luther University Halle-Wittenberg.


Whittington, D., McClelland, E. (1992). Opportunities for regional and inter-

Appendix: Dominant Independent Patterns of GLDAS TWS, and TRMM Rainfall for the entire Nile Basin

FIGURE A1

FIGURE A2
<table>
<thead>
<tr>
<th></th>
<th>Area</th>
<th>Catchment</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Victoria</td>
<td>258,000 km²</td>
<td>Lakes Kyoga (75,000 km²)</td>
<td>Head Waters of the White Nile</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Albert, Elbert, George (48,000 km²)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Semiliki Basin</td>
<td></td>
</tr>
<tr>
<td>Barrel-Ghazel</td>
<td>526,000 km²</td>
<td>Congo-Nile River divide</td>
<td>About 96%(^b) of basin runoff and precipitation is lost to</td>
</tr>
<tr>
<td>(BEG)</td>
<td></td>
<td>Large area of low slope</td>
<td>evaporation and leakage to swamp</td>
</tr>
<tr>
<td>Ethiopian</td>
<td>300,000 km²</td>
<td>Lake Tana Region (20000 km²)</td>
<td>Head waters(^a) of the Blue Nile contributing about 65% of the</td>
</tr>
<tr>
<td>Highland</td>
<td></td>
<td>Upper Blue Nile region (150,000 km²)</td>
<td>Nile waters.</td>
</tr>
<tr>
<td>(EH)</td>
<td></td>
<td>Lower Blue Nile region (60,000 km²)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dinda Rahad region (60,000 km²)</td>
<td></td>
</tr>
<tr>
<td>Egypt Desert</td>
<td></td>
<td>Lake Nasser (formed by Aswan dam)</td>
<td>Water loss due to evaporation</td>
</tr>
<tr>
<td>Region</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Yates (1998)  
\(^b\) Conway and Hulme (1993)
Table 2: Correlation coefficient between independent patterns of TWS derived from GRACE and climate variability of IOD (in bold) and ENSO (in normal text) over the Nile sub-basins. Correlations are computed at 95% level of confidence. The insignificant values are marked.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barh-El-Ghazal IC1 GRACE</td>
<td>+0.18 (insignificant)</td>
</tr>
<tr>
<td>Ethiopian Highlands IC2 GRACE</td>
<td>+0.31</td>
</tr>
<tr>
<td>(with the red Sea and the lake’s signals)</td>
<td>+0.54</td>
</tr>
<tr>
<td>Ethiopian Highlands IC2 GRACE</td>
<td>+0.47</td>
</tr>
<tr>
<td>(without the red Sea and the lake’s signals)</td>
<td>+0.59</td>
</tr>
<tr>
<td>Lake Victoria Basin IC3 GRACE</td>
<td>+0.48</td>
</tr>
<tr>
<td>(with the red Sea and the lake’s signals)</td>
<td>0.56</td>
</tr>
<tr>
<td>The Nasser region IC4 GRACE</td>
<td>+0.13 (insignificant)</td>
</tr>
<tr>
<td>(with the red Sea and the lake’s signals)</td>
<td>−0.10 (insignificant)</td>
</tr>
<tr>
<td>The Nasser region IC4 GRACE</td>
<td>+0.33</td>
</tr>
<tr>
<td>(without the red Sea and the lake’s signals)</td>
<td>+0.30</td>
</tr>
</tbody>
</table>
Figure 1: The Nile Basin (brown shaded region) with the major sub-basins used in the study shown.
Figure 2: Satellite altimetry-derived signals for Lake Victoria (after smoothing with the DDK2 filter (Kusche et al., 2009) and conversion to equivalent water thickness (EWT)). Both time series are centered with respect to their temporal means. The altimetry-derived EWT signals represents a smoother pattern compared to the GRACE signals, which might be due to the fact that it contains only water level changes of Lake Victoria and not water storage changes over the surrounding regions of the lake. Error-bars for the GRACE-derived TWS are obtained by propagating the errors of spherical harmonics, after DDK2 filtering, to TWS without considering the covariances. Computing the error-bars for altimetry-derived TWS is done by considering the accuracy provided in LEGOS data (Crétaux et al., 2011)
Figure 3: (top) Root mean squares of the introduced water storage changes over the major lakes of the Nile Basin, soil moisture changes of the basin and non-tidal water storage changes of the Red Sea; (Bottom) The first three independent modes, derived from ICA. The results show that the strong signal of Lake Victoria (IC3) can successfully be separated from those of the Red Sea and Lake Nasser (IC1) and those of soil moisture (IC2).
Figure 4: (left) Correlation between GRACE and TRMM; (center) phase lag between GRACE and TRMM in months; and (right) correlation between GRACE and GLDAS. The results show high rainfall impacts on TWS changes over the tropical regions, Bar-el-Ghazal (BEG) and parts of Ethiopian Highlands (EH).
Figure 5: ICA decomposition of GRACE TWS signal within the Nile Basin using the proposed ICA method of Forootan and Kusche (2012, 2013). The upper panels are the spatial pattern of each IC. Note that the Nile Basin’s TWS signal is separated (localized) by the ICA method into 4 significant spatially independent components (BEG (left), EH (second from left), LVB (third from left) and Red Sea (right). Together, these four signals computed over the Nile Basin account for 92% of cumulative total variance of TWS changes. In the lower panel, their corresponding time series (ICs) overlaid on smoothed time series of the loading, as well as ENSO and IOD indices.
Figure 6: Dominant independent patterns of GRACE TWS after removing the contribution of Lakes Tana and Victoria surface water signals. Spatial patterns show the concentration of the remaining signals (after removal) over the Ethiopian Highlands (panel A) and the western part of Lake Victoria Basin (panel B). Panels C and D show their corresponding time series (ICs) overlaid on smoothed time series of the loading and ENSO and IOD.
Figure 7: Dominant independent pattern of GRACE-TWS changes for the Nasser region.  
A) Spatial pattern of IC4 derived from GRACE-TWS changes after correction for the water storage changes of the Red Sea; B) the corresponding temporal evolution of (A) and its comparison with the ENSO and IOD indices; C) comparison of IC4 in (B) with the signal of the Red Sea and Lake Nasser; and D) an overview of IC4 after removing the signal of the Red Sea and its comparison with the signal of Lake Nasser. We should mention here that the Lake Nasser TWS of (C) and (D) represent the same quantity. To enhance the visual comparison, that of (D), is however, vertically shifted to the mean of IC4.
The ICA decomposition of GLDAS water storage data within the Nile Basin accounting for 86% of cumulative total variance of GLDAS-TWS changes. The linear rates of TWS changes corresponding to each sub-basin are also reported in the figure. IC2 and IC3 of GLDAS are comparable to those of GRACE, while IC4 of GLDAS is concentrated over the eastern part of the LVB. However, no concentration over the northern part of the basin (e.g., IC6 of GRACE) is found from GLDAS data.
A2: ICA decomposition of TRMM derived rainfall data within the Nile Basin accounting for 91% of cumulative total variance of rainfall changes. IC3 is localized over LVB, IC4 over the EH and IC5 over the BEG region.
Highlights

1. TWS of independent sub-basins within the Nile Basin are extracted
2. Ethiopian Highlands shows an overall declining trend in its rainfall during 2002-2011
3. Lake Nasser loses water storage through evaporation and over-extraction
4. Bar-el-Ghazal does not show a dominant multi-year change in water storage
5. ENSO was the dominant climate variability of the Nile Basin during 2002-2011