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Potential impacts of climate and environmental change on the stored water of Lake Victoria Basin and economic implications

J. L. Awange,[1] R. Anyah,[2] N. Agola,[3] E. Forootan,[4] and P. Omondi[5]

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[1] The changing climatic patterns and increasing human population within the Lake Victoria Basin (LVB), together with overexploitation of water for economic activities call for assessment of water management for the entire basin. This study focused on the analysis of a combination of available in situ climate data, Gravity Recovery And Climate Experiment (GRACE), Tropical Rainfall Measuring Mission (TRMM) observations, and high resolution Regional Climate simulations during recent decade(s) to assess the water storage changes within LVB that may be linked to recent climatic variability/changes and anomalies. We employed trend analysis, principal component analysis (PCA), and temporal/spatial correlations to explore the associations and covariability among LVB stored water, rainfall variability, and large-scale forcings associated with El-Niño/Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). Potential economic impacts of human and climate-induced changes in LVB stored water are also explored. Overall, observed in situ rainfall from lake-shore stations showed a modest increasing trend during the recent decades. The dominant patterns of rainfall data from the TRMM satellite estimates suggest that the spatial and temporal distribution of precipitation have not changed much during the period of 1998–2012 over the basin consistent with in situ observations. However, GRACE-derived water storage changes over LVB indicate an average decline of 38.2 mm/yr for 2003–2006, likely due to the extension of the Owen Fall/Nalubale dam, and an increase of 4.5 mm/yr over 2007–2013, likely due to two massive rainfalls in 2006–2007 and 2010–2011. The temporal correlations between rainfall and ENSO/IOD indices during the study period, based on TRMM and model simulations, suggest significant influence of large-scale forcing on LVB rainfall, and thus stored water. The contributions of ENSO and IOD on the amplitude of TRMM-rainfall and GRACE-derived water storage changes, for the period of 2003–2013, are estimated to be ~2.5 cm and ~1.5 cm, respectively.

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1. Introduction

[2] Freshwater, the most fundamental natural resource for human beings, is required in abundance for drinking, agriculture, and all forms of socio-economic development. Its stored potential (surface, groundwater, soil moisture, ice, etc.) is increasingly facing challenges from climate change as well as anthropogenic activities. That current and future climate change is expected to significantly impact the freshwater systems including rivers, streams, and lakes, in terms of flow and direction, timing, volume, temperature, and its inhabitants has been documented in numerous publications [e.g., *Bates et al.*, 2008; *Palmer et al.*, 2008]. Changes in the freshwater system, both in terms of quality and quantity, resulting from both natural climate variability (e.g., rainfall patterns) and change, and other anthropogenic influences such as excessive water withdrawals and construction of dams for hydropower generation in the upstream will have significant consequences on the ecosystem and the people depending on them [e.g., *Palmer et al.*, 2008]. The conditions are expected to get worse for hugely populated basins such as Lake Victoria Basin (LVB) [see e.g., *Hecky et al.*, 2010].

[3] Lake Victoria, the second largest freshwater body on Earth, is a source of freshwater and livelihood for more than 30 million people living around it [*Awange and Ong'ang'a*, 2006] and indirectly supports another 340 million people along the Nile Basin [*Sutcliffe and Parks*, 1999] being the source of the White Nile. Lake Victoria Basin (LVB, Figure 1) constitutes an area of 193,000 km^2 and extends over Burundi (7.2%), Kenya (21.5%), Rwanda (11.4%), Tanzania (44%), and Uganda (15.9%) [*Awange*

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[1] Western Australian Centre for Geodesy and Institute for Geoscience Research, Curtin University, Perth, Western Australia, Australia.

[2] Department of Natural Resources and the Environment, University of Connecticut, Storrs, Connecticut, USA.

[3] Graduate School of Global Studies, Doshisha University, Kyoto, Japan.

[4] Institute of Geodesy and Geoinformation, Bonn University, Bonn, Germany.

[5] IGAD Climate Prediction and Applications Centre, Nairobi, Kenya.

Corresponding author: J. L. Awange, Western Australian Centre for Geodesy and The Institute for Geoscience Research Curtin University, Perth, WA 6102, Australia. (J.Awange@curtin.edu.au)

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Figure 1. Lake Victoria Basin and in situ rainfall stations (red) used in the study [Source: *Kayombo and Jorgensen*, 2006].

and Ong'ang'a, 2006]. The basin acts as a constant source of water to the lake through its massive catchment area and its ability to influence the regions' seasonal rainfall. In the last decade, however, the stored waters within LVB have come under immense pressure from climate change and anthropogenic factors that resulted in significant fluctuations. However, the lake level remained above average since the early 1960s [*Nicholson*, 1998, 1999] till the early 2000s. Discharge estimates from the lake for the period 1950–2005 show that the net balance between recharge and discharge remained relatively stable over the estimation period [*PPA*, 2007]. A decreasing trend in the lake's level in the past decade as shown, e.g., by *Kull* [2006], *Riebeek* [2006], *Swenson and Wahr* [2009], and *Awange et al*. [2008a], however, is attributed equally to overabstraction and natural climate change such as evaporation [*PPA*, 2007; *Sutcliffe and Petersen*, 2007; *Awange et al*., 2008b; *Swenson and Wahr*, 2009].

[4] Lake Victoria Basin is characterized by modified equatorial type of climate with substantial rainfall occurring throughout the year, particularly over the lake surface, to semiarid type characterized by intermittent droughts over some nearshore regions [e.g., *Anyah et al*., 2006]. The seasonal rainfall over the basin is further characterized by a bimodal cycle, just like most areas of East Africa, and is controlled mainly by the north-south migration of Inter Tropical Convergence Zone (ITCZ), a quasi-permanent trough that occurs over Lake Victoria [e.g., *Asnani*, 1993] due to locally induced convection, orographic influence, and land-lake thermal contrast, which modulates rainfall pattern over the lake and hinterlands. The large-scale precipitation over the lake is mainly initiated from the easterly/southeasterly (Indian Ocean) monsoon flow that transports maritime moisture into the interior of East Africa. The humid Congo air mass has also been linked to significant rainfall amounts received over the western and northwestern parts of the lake [*Asnani*, 1993]. Large-scale winds over the Lake Basin are mainly easterly trades most of the year. Superimposed on this basic flow regime are the south-easterly (SE) or north-easterly (NE) monsoons that are mostly driven toward, and often converge over, the ITCZ location. The strength of the monsoons also depends on the subtropical anticyclones over the Arabian Sea (Arabian high pressure cell) and southwestern Indian Ocean (Macarene high pressure cell).

[5] In terms of interannual variability, Lake Victoria Basin climate is characterized by periodic episodes of anomalously wet/dry conditions with some of the memorable events including the 1961/1962 and 1997/1998 floods that left behind a huge trail of damage to property and infrastructure. The 1961/1962 floods were associated with a strong zonal SST gradient over the equatorial Indian Ocean and midtroposphere westerly flow from Tropical Atlantic [*Anyamba*, 1984; *Anyah and Semazzi*, 2006, 2007]. It is noteworthy that 1997/1998 floods coincided with one of the warmest ENSO episodes (strongest El Niño) of the last century as well as very strong IOD mode. Hence, the interannual variability of the Lake Basin is also closely linked to the SST anomalies over the global ocean basins [*Omondi et al.*, 2012, 2013].

[6] On the one hand, climate change influences rainfall and temperature patterns thereby affecting LVB's stored water. This is attributed to the fact that more than 80% of LVB's water source is derived directly from the seasonal precipitation [e.g., *Awange and Ong'ang'a*, 2006] and almost an equivalent amount of the precipitation is lost to

evaporation [*Yin and Nicholson*, 1998; *Sewagudde*, 2009]. The temperature in the LVB region is projected to increase by 3–4°C by the end of this century without much change in the rainfall regime, leading to a significant downward trend in the Lake's net Basin supply as a result of enhanced evaporation [*Sewagudde*, 2009] as well as increased water temperatures. Impacts of climate change on LVB have been reported [e.g., *PPA*, 2007; *Sutcliffe and Petersen*, 2007; *Swenson and Wahr*, 2009; *Lejju*, 2012].

[7] On the other hand, on anthropogenic influence on LVB, *Yin and Nicholson* [1998] characterized most of the LVB's catchment areas as semiarid zones, with exception of areas close to the lake, and hence the catchments ability to discharge water into Lake Victoria is expected to decrease as a result of increased abstraction demand for agricultural and industrial activities. This, in addition to declining lake water quantity and quality due to increasing population will thus have serious impacts on the regional water requirement, domestic food supplies, and global food trade [e.g., *Geheb and Crean*, 2003; *Awange et al*., 2007; *Johnson*, 2009].

[8] Combined, the impacts of both climate change and other anthropogenic factors on LVB's total water storage (TWS) are having a toll on the economic as well as the environment of the region. For instance, there are already signs of declining fish trades [*Geheb and Crean*, 2003] and access to freshwater in the LVB leading to environmental scarcity [e.g., *Mwiturubani*, 2010; *Canter and Ndegwa*, 2002]. Change of fish community and loss of phytoplankton [e.g., *Geheb and Crean*, 2003; *Hecky et al*., 2010] are some impacts of climate change and anthropogenic influences on the lakes water quality, questioning the quality and health of the food. Lake Victoria's outflow is determined by the "agreed curve" drawn between Egypt and Uganda, which also determines the level of hydropower generation. The current and more alarming anthropogenic stress is the increasing demand for power as a result of increasing population in the basin area [*Mutenyo*, 2009; *PPA*, 2007]. The impact of hydropower plants along the Nile river are found to be largest during the drought seasons (or years) and is therefore, expected to put more pressure on the lake with increasing hydropower plants [e.g., *Mutenyo*, 2009; *Hecky et al*., 2010]. Recent studies on climate variability and change over the LVB and fluctuations of Lake Victoria levels show some worrying scene of drought patterns and receding lake levels, which are both attributed to natural climate change and increasing human influence [e.g., *Yin and Nicholson*, 1998; *Awange et al*., 2008a, 2008b, 2013; *Swenson and Wahr*, 2009; *Sewagudde*, 2009]. Thus, it is very important to monitor the basin's hydrological cycle using the up-to-date technology and methods to inform the policy makers and politicians, who plays the most important role in managing the regional water resource. All these poses a significant environment and economic challenge to the East African region as a whole, leading to various levels of domestic and interstate conflicts [see e.g., *Canter and Ndegwa*, 2002].

[9] This contribution examines the changes of total water storage (surface, groundwater, and soil moisture) caused by climate variability and extremes over the recent decade (2003–2013) over LVB and the potential economic impacts. To achieve this, we employ freely available global high resolution satellite data sets of Tropical Rainfall Measuring Mission (TRMM) rainfall estimates and Gravity Recovery And Climate Experiment (GRACE) time-variable gravity fields [*Tapley et al*., 2004a, 2004b] coupled with outputs from various Regional Climate Models (RCMs) in addition to analysis of observed in situ rainfall data over specific stations within the lake's perimeter to study trends of climate over the basin.

[10] The rest of the study is organized as follows. Section 2 presents a brief overview of the various data sets used and discusses the methods employed to investigate the impacts of climate variability and extremes on stored water potential of LVB. The results are presented and discussed in section 3 while section 4 concludes the report.

2. Data Sets and Methodology

[11] This section gives a brief overview of the various data sets employed in this study. These include observed in situ data, Gravity Recovery And Climate Experiment (GRACE) and Tropical Rainfall Measuring Mission (TRMM). Section 2.1 gives brief highlights on each data set used.

2.1. Rainfall Data (1960–2012)

[12] Monthly observed in situ precipitation data for stations along Lake Victoria Basin (see Figure 1) were employed in this analysis. There are a number of other meteorological stations within the Lake Victoria Basin, but only those representatives of their climatological zones with homogeneous anomalies were used. The annual rainfall total was computed through accumulation of the monthly observed data. These data sets were first subjected to quality control and homogeneity tests [see e.g., *Peterson et al*., 1998; *Omondi et al*., 2012], before being analyzed. The slopes of linear trends from the annual rainfall total for the common period 1921–2012 were computed using least-squares regression analysis while statistical significance assessed using Student's *t* test [*Awange et al*., 2008b]. Linear regression model was applied to the accumulated annual rainfall total for various stations used for the study.

2.2. Tropical Rainfall Measuring Mission (TRMM)

[13] The rainfall measurements employed in this work are a product derived largely from observations made by the Tropical Rainfall Measuring Mission (TRMM) [*Kummerow et al*., 2000]. TRMM products have been employed in a number of studies of African precipitation where they have been found to be adequate when compared with ground truth observations [e.g., *Nicholson et al*., 2003; *Owor et al*., 2009]. The product employed in this work is referred to as the *TRMM and Other Precipitation Data Set* (denoted as 3B43), and covers the period 1998–2013. 3B43 provides monthly rainfall (average hourly rate) between latitudes 50°N/50°S over a 0.25° × 0.25° grid. It is derived not only from TRMM instruments, but also a number of other satellites and ground-based rain-gauge data. Over time, the products produced from the TRMM observations are updated as the processing techniques and methods for integrating the different data sets are improved upon. In this work we use the latest version, number 7, which has been found to be a significant improvement over the previous version 6 owing to such changes as the use of

additional satellites and a superior means of incorporating rain-gauge information from the Global Precipitation Climatological Centre [*Huffmann and Bolvin*, 2012; *Fleming and Awange*, 2013].

2.3. Gravity Recovery And Climate Experiment (GRACE)

[14] The Gravity Recovery And Climate Experiment (GRACE) is a United States (National Aeronautics and Space Administration, NASA) and German (Deutsche Zentrum für Luft-und Raumfahrt, DLR) space mission which has been providing products that describe the temporal variation of the Earth's gravity field arising from mass movements within the Earth's system. Level-2 time-variable gravity field products of GRACE have been frequently used to study the Earth's water storage variations [see e.g., *Awange et al.*, 2008; *Forootan and Kusche*, 2012; *Forootan et al.*, 2012]. This study uses the latest release five (RL05) monthly GRACE solutions, provided by the German Research Centre for Geosciences (GeoForschungsZentrum, GFZ) [*Dahle et al.*, 2012], covering 2003–2013.

[15] For computing monthly total water storage (TWS) fields over the LVB basin, the following items are considered:

[16] 1. GRACE level-2 products contain correlated errors among higher order spherical harmonics, known as the north-south striping pattern in spatial domain [*Kusche*, 2007]. In order to remove stripes, we applied the decorrelation filter of DDK3 [*Kusche et al.*, 2009] to the GFZ-RL05 solutions. The filtered solutions can also be downloaded from http://icgem.gfz-potsdam.de/ICGEM/TimeSeries.html. Evaluation of the DDK filter for computing correct water storage variations is addressed, e.g., in *Werth et al.* [2009].

[17] 2. Residual gravity field solutions with respect to the temporal average of 2003–2013 were computed.

[18] 3. The residual coefficients were then convolved with a basin function, while considering the basin boundary of Figure 1. For computing the basin function, we assumed a uniform mass distribution with the value of one inside the LVB basin and no mass outside the basin ($S1 = 1$, is a uniform mass in the basin). Then, we transformed the uniform mass into spherical harmonics. The obtained coefficients are filtered with the same DDK3 filter as was applied for GRACE products.

[19] 4. In order to account for leakages [see, e.g., *Fenoglio-Marc et al.*, 2006, 2012], the total surface mass of the basin was calculated from the basin function coefficients (S2, synthesized uniform mass in the LVB basin). The ratio of S1/S2 reflects the effect of the truncation of the spherical harmonics as well as signal attenuation due to filtering GRACE products over LVB.

[20] 5. The derived ratio is multiplied by coefficients in item 2 and the results were transformed into $0.5^\circ \times 0.5^\circ$ TWS maps within LVB, following *Wahr et al.* [1998].

2.4. CRU Data

[21] The University of East Anglia Climate Research Unit (CRU) gridded observational data comprise 1200 monthly observed climate from 1901 to 2000. CRU data are derived from gauge observations over land areas only and are interpolated on a regular grid of $0.50^\circ \times 0.50^\circ$ [*Mitchell et al.*, 2004]. The data sets contain five climatic variables including precipitation, surface temperature, diurnal temperature range (DTR), cloud cover, and vapor pressure. In the present study, we only utilize monthly mean surface temperature and precipitation to complement the available station-based observations.

2.5. Regional Climate Simulations

[22] In this study, we present results of simulated rainfall climatology during the recent decades from four state-of-the-art high resolution Regional Climate Models (a random sample from the Coordinated Regional Downscaling Experiment (CORDEX)) a group of models being used in CORDEX (http://wcrp-cordex.ipsl.jussieu.fr/). CORDEX Africa Project (http://start.org/cordex-africa/about/) used different RCMs to simulate rainfall over the whole Africa domain. The four RCMs data from the CORDEX archive used in constructing simulated climatology over the LVB were WRF, MPI, CRCM5, and PRECIS. The data is from 1989 to 2008 (20 years). The spatial resolution for RCMs-CORDEX is 50 km and for our study, data were extracted for the LVB domain stretching from 31°E to 36°E, and 4°S to 2°N. Details on these RCMs are explained in *Nikulin et al.* [2012].

[23] Given the importance of rainfall in the water balance of the LVB, in the present study we only concentrate in comparing the model versus observations (TRMM 3B43-V7 and CRU). We also evaluate how the model simulates the impact of large-scale forcings on the seasonal and interannual variability of LVB rainfall (i.e., influence of IOD and ENSO during the years 2005 and 2006, respectively). In order to understand the IOD and ENSO influence, we also computed spatial correlations between Nino3.4 and IOD indices for both model and observed (TRMM) data. Knowing the temporal pattern of ENSO and IOD from the indices, their contributions were coestimated considering linear trends as well as the annual and semiannual components in the TRMM-derived rainfall and GRACE-derived TWS changes from 2003 to 2013.

3. Results and Discussions

3.1. Rainfall Variability Analysis

[24] The trend analysis results for precipitation over the basin are shown in Figure 2. Stations located within the Lake Victoria Basin generally showed modest increase in rainfall trends (e.g., see Figures 2a–2d). The increase in trends shown by these stations is, however, not significant at 95% confidence level when Student's t test is applied. We further employed the statistical method of Principal Component Analysis (PCA) [*Preisendorfer*, 1988] to TRMM data to isolate the dominant spatial and temporal patterns of rainfall variability over the LVB during the recent years. We preferred using the TRMM-rainfall estimates here given the more complete spatial coverage, albeit over a relatively short period. To extract the period with relatively more rainfall, we summed up the rainfall values of each monthly grids and showed them with respect to their corresponding month in Figure 3. Impacts of the EL-Niño Southern Oscillation phenomenon can be seen, e.g., in 2006–2007 and 2011–2012.

[25] Applying PCA to rainfall data of LVB, we found four dominant EOFs and PCs that are shown in Figure 4.

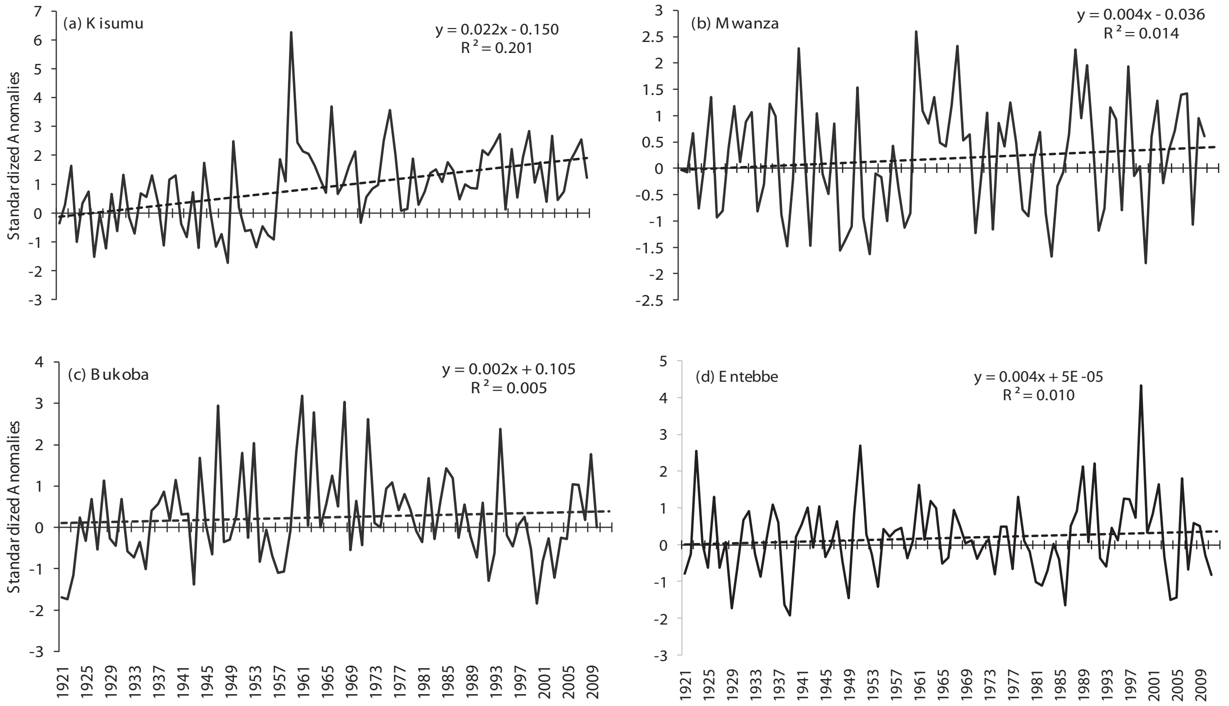

Figure 2. Rainfall trends for some stations in the Lake Victoria Basin.

EOF1 and PC1 (representing 63% of total variance of the rainfall) show a superposition of the annual and seasonal variabilities. The amplitude of the signal in some years such as that of 2007 is amplified as a result of El-Niño. EOF2 and PC2 representing 13% of total rainfall are also related to the annual variation with the same dipole structure of the annual TWS changes in Figure 7. We found a lag of 1 month between PC2 of TRMM and PC2 of TWS changes. PC3 shows a summation of interannual changes and a linear trend over the basin. Considering the structure of EOF3, which is negative over the northwest and positive over the southeast, we estimate, respectively, a rainfall rate of -2.0 and 2.8 mm/yr over them, for the period of 2003–2013. The derived trends, however, were not statistically significant. We do not interpret the fourth mode of PCA on rainfall changes (EOF4 and PC4) here, since the temporal pattern is quite noisy and they represent only 3% of variance in rainfall.

3.2. Simulated Climatology of LVB (1989–2008)

[26] The observed bimodal rainfall pattern over the LVB (31.5–34°E; 2.5°S–1°N) is well reproduced by three of the four CORDEX Regional Climate Models (RCMs) as shown in Figure 5. However, the MPI RCM captures the bimodal rainfall regime but underestimates the peaks during MAM and OND seasons. This level of RCMs differences (uncertainties) in reproducing the LVB spatial and temporal mean patterns of precipitation presents a challenge in using numerical (theoretical) modeling techniques to understand climate-hydrology connections as well as water level/storage variability over LVB. The RCMs inability to reproduce variability of some peculiar rainfall features of the LVB climate has been linked to incomplete representation/parameterization of localized convective and boundary layer processes that exert significant influence on the spatiotemporal distribution of LVB rainfall [*Song et al.*, 2006; *Sun et al.*, 1999; *Anyah et al.*, 2006; *Anyah and Semazzi*, 2009].

[27] In Figure 6, the Canadian Regional Climate Model version 5 (CRCM5), compared to TRMM estimates, overestimates over-lake seasonal rainfall amounts for both MAM and OND seasons. On the other hand, the PRECIS model as well as the other two models (not shown) consistently simulate drier conditions over the LVB; in some places underestimating the rainfall totals by nearly 100% of the observed (TRMM) seasonal total, especially during the March–May (MAM). However, the CRCM5 captures the OND seasonal mean rainfall pattern quite well compared to TRMM, and also consistent with the dominant EOF loadings of TRMM in Figure 4. The PRECIS model also reproduces the observed spatial distribution of rainfall during OND although the simulated center of rainfall maximum is over the northeastern quadrant of the Lake as opposed to

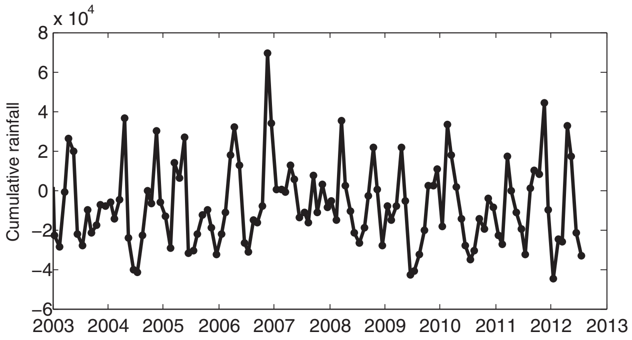

Figure 3. An overview of the cumulative rainfall, derived from each month of TRMM data over LVB, for the period of 2003–2013.

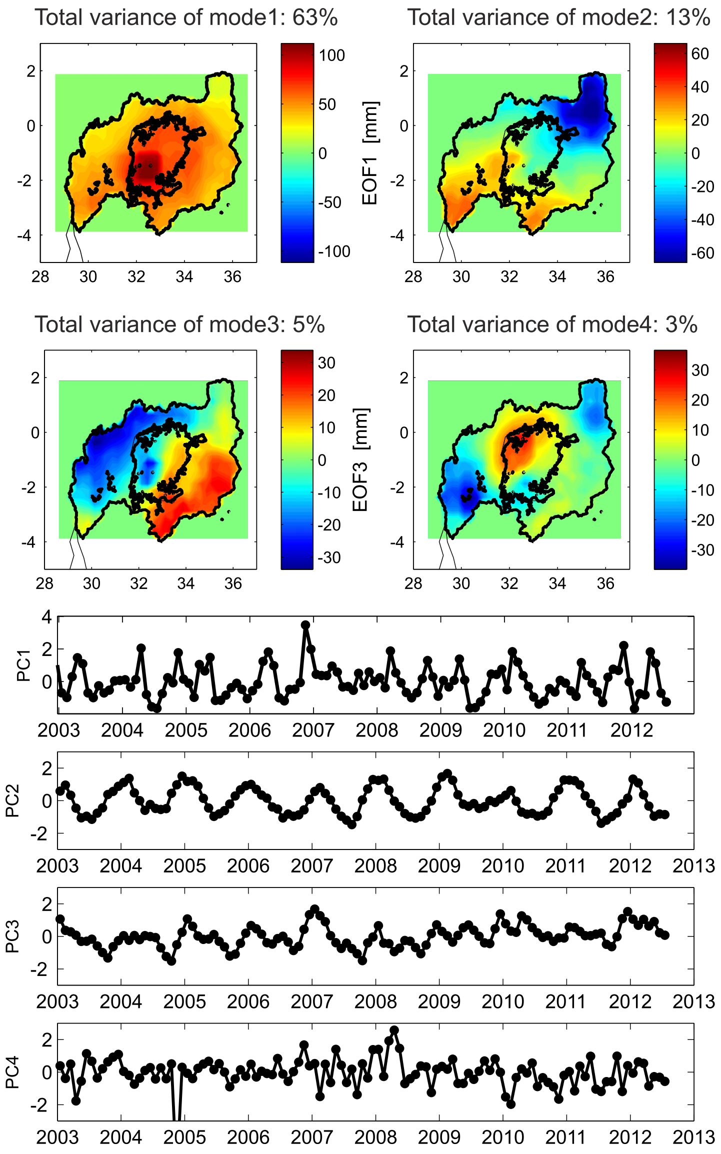

Figure 4. PCA decomposition of rainfall changes derived from TRMM, over LVB. EOFs are rainfall anomaly maps and PCs are their corresponding unit-less temporal patterns.

southwestern and western quadrants as in TRMM estimates and CRCM5 simulation.

3.3. GRACE Total Water Storage Over LVB

[28] We then employed PCA on TWS to examine whether the observed and simulated patterns of climate variability discussed in the previous section are consistent with the water storage variability derived from GRACE data. As a result, its first two dominant EOFs and PCs are shown in Figure 7, where EOF1 and PC1 represent 82% of total variance in TWS changes and EOF2 and PC2 represents 14%. EOF1 shows a strong anomaly all over the basin, while its corresponding PC1 shows the dominant trend of the basin. Using a linear regression, we found an average mass decline of 38.2 and increase of 4.5 mm/yr over the LVB, respectively, for the periods of 2003–2007 and 2007–2013. EOF2 shows a spatial north-south dipole structure, which as PC2 indicates, corresponds to the

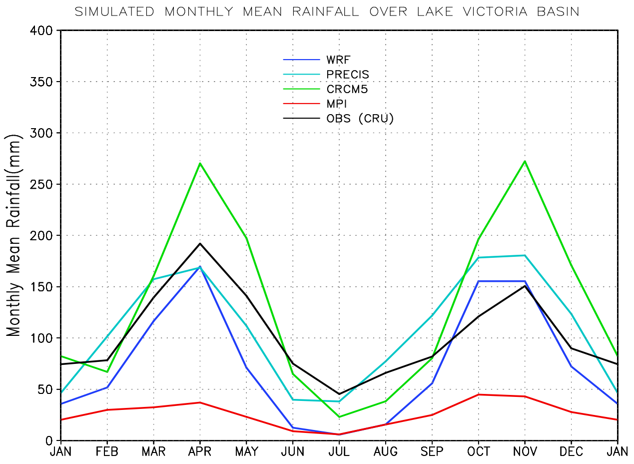

Figure 5. Mean annual cycle of precipitation (mm) over Lake Victoria Basin (31.5–34°E, −2.5°S to 0.5°N).

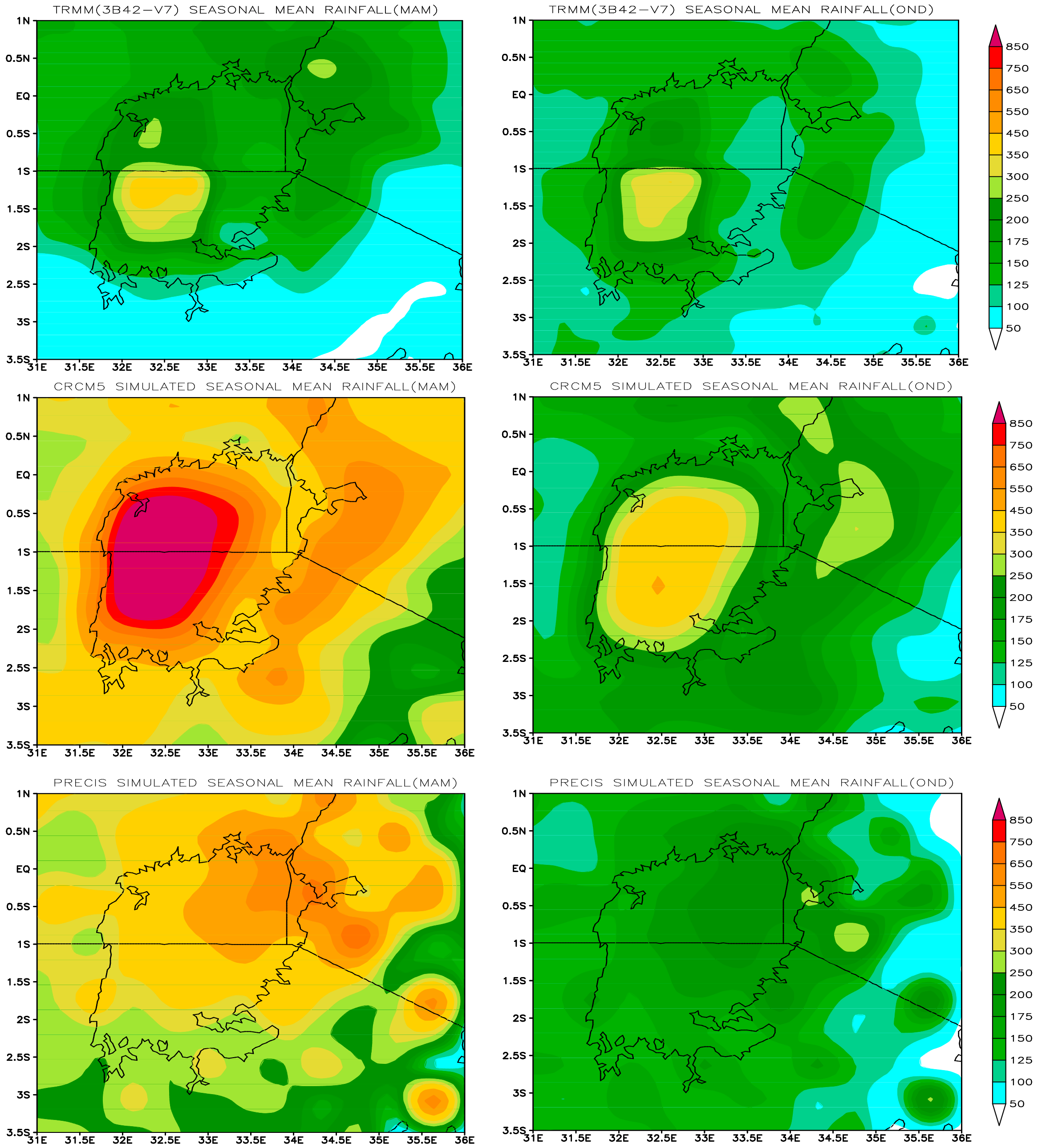

Figure 6. Spatial pattern of seasonal mean rainfall (mm) over LVB. (left) March–May season. (right) October-December season.

annual changes of TWS over the basin. The TWS decline of 2003–2007 is attributed to the extension of the Owen Falls (Nalubale) dam as stated [e.g., *Awange et al.*, 2008a; *Swenson and Wahr*, 2009]. The positive rate of 2007–2013 is likely due to the positive impact of El Niño in the years 2007 and 2009/2010. This result is supported by rainfall analysis of section 3.

3.4. Influence of ENSO and IOD on Interannual Variability of LVB Rainfall

[29] Some previous studies over equatorial eastern Africa (including LVB) have shown that local forcings modulate regional climate by either amplifying or suppressing the anomalies triggered by perturbations in the large-scale circulations that are propagated through global teleconnections such as El-Niño/Southern Oscillation and east-west sea surface temperature (SST) gradient over equatorial Indian Ocean (i.e., IOD mode) [*Saji et al.*, 1999; *Indeje et al.*, 2000; *Schreck and Semazzi*, 2004; *Omondi et al.*, 2013; *Anyah and Semazzi*, 2004, among others]. ENSO and IOD have thus been indicated as significant triggers of some of the past extreme LVB rainfall anomalies (floods and droughts).

[30] In the present study, we show in Figure 8 the observed and simulated rainfall anomalies during 2005 and 2006, associated with fairly strong La Niña and El Niño/IOD conditions, respectively. Generally, the apparent ENSO influence on the spatial variability of LVB rainfall is

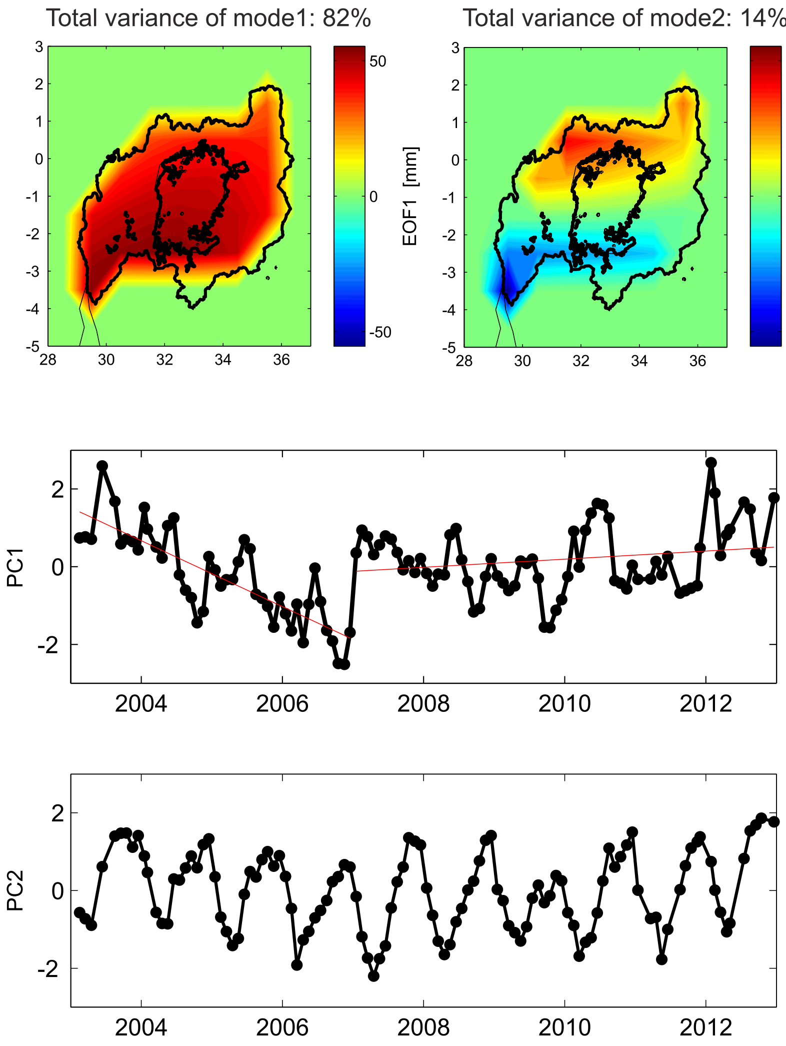

Figure 7. PCA decomposition of TWS changes over LVB. EOFs are counted as anomaly maps that show the spatial distribution of TWS changes within the basin. Corresponding PCs are temporal variations which are scaled with their standard deviations to be unit-less.

manifest, with more widespread below normal rainfall amounts during the OND season (2005) and the opposite during 2006 season (based on 1989–2008 average). Overlake rainfall is more depressed during La Niña (2005), but there is a modest increase during El Niño years (2006 and 2010), although TRMM estimates show significant increases over the western and northern quadrants of the Lake. This feature is clearly reproduced by all the four CORDEX models, compared to TRMM estimates. Given the recent improvements in ENSO prediction, with lead times over 6 months, the apparent link between LVB rainfall and ENSO can have very practical application for LVB water resources availability and governance.

[31] In Figure 9, we show the spatial correlations between ENSO (Nino3.4 index) and LVB TRMM on the one hand, and simulated monthly rainfall totals on the other hand during the OND season. In October (Figure 9, top), statistically significant correlation between Nino3.4 and TRMM (3B43-V7) during 1998–2008 is observed over the western parts of the Lake as well as the northeastern shores (Winam Gulf and surrounding areas). In contrast, significant *r* values between Nino3.4 and simulated rainfall tend to be more widespread, especially over the northern sector of the Lake. Similar correlation patterns are derived from TRMM during November (Figure 9, middle), but Nino3.4 index correlation with the simulated rainfall show very weak correlations ($r \sim 0$), especially over the lake surface. The spatial correlation pattern in December (Figure 9, bottom) for both TRMM and model are somehow similar to the pattern in October (Figure 9, top).

[32] A conspicuous similarity in the monthly spatial correlation patterns between IOD and rainfall (Figure 10), and those shown in Figure 9 is unmistakable. This apparently implies that cooccurrence of IOD and ENSO events exert significant influence on LVB rainfall, and hence significantly influence climate-sensitive socio-economic activities (see section 3 over the lake and its hinterland).

[33] In order to estimate the impact of ENSO and IOD on the variability of rainfall and thus stored water, we assumed the normalized temporal patterns of the Nino3.4 and IOD indices as known. Then, we coestimated their contributions, beside a linear trend as well as the annual and

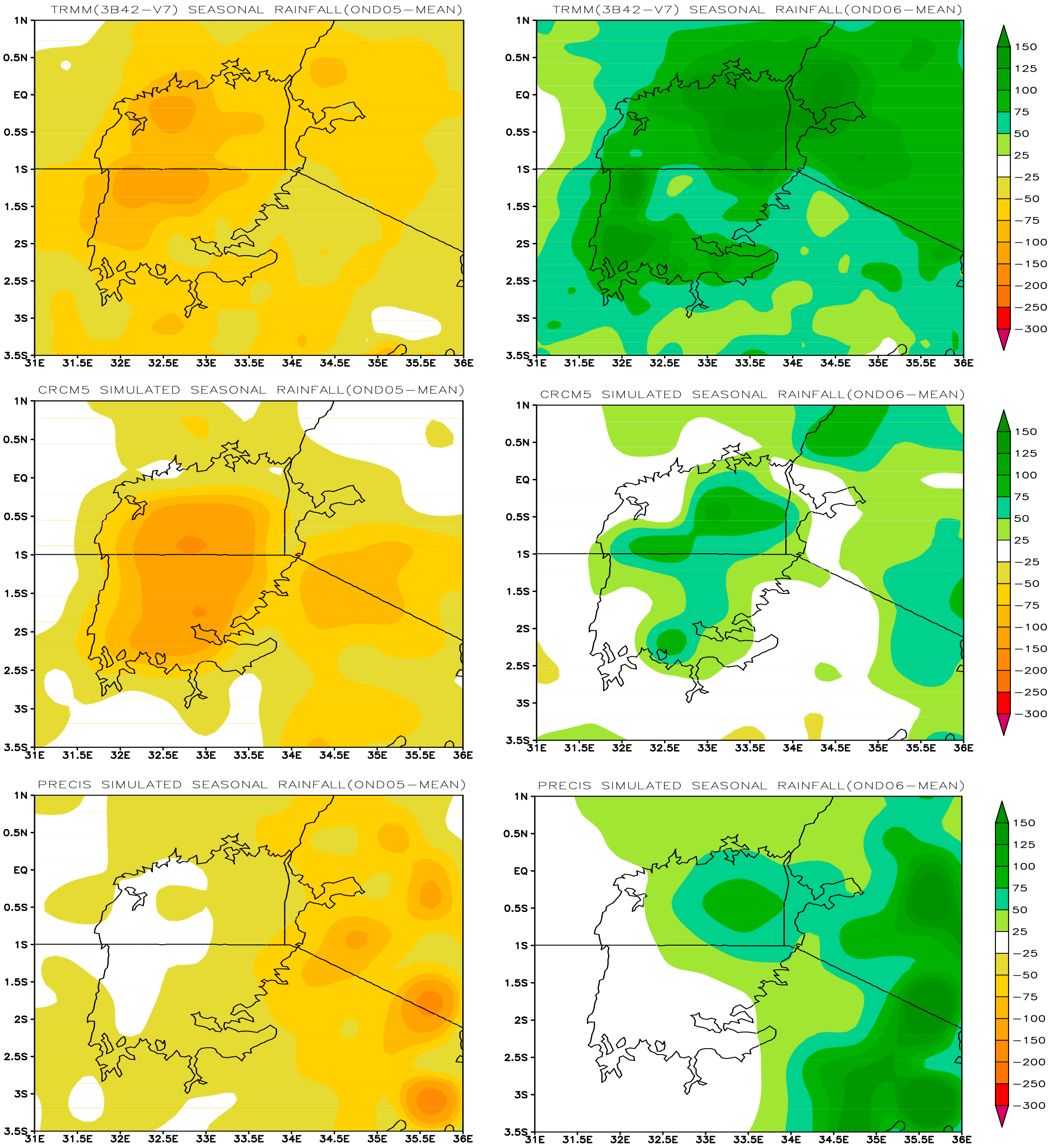

Figure 8. (left) Spatial pattern of 2005 (La Nina), and (right) 2006 (El Nino) seasonal rainfall anomalies (mm) from long-term mean over LVB.

semiannual components, in the variability of TRMM-rainfall and GRACE-TWS, over 2003–2013. Thus, we assumed that the dominant temporal behavior of the rainfall and TWS changes is represented by $[a, b.t, c.sin(2\pi t), d.cos(2\pi t), e.sin(4\pi t), f.cos(4\pi t), g.\bar{E}(t-\phi_{ENSO}), h.\bar{I}(t-\phi_{IOD})]$, where t is time in year (2003–2013), $\bar{E}$ and $\bar{I}$, respectively, contain the normalized ENSO and IOD indices and ϕ_{ENSO} and ϕ_{IOD} are the phase lags in year between the indices and the rainfall/TWS time series. The contributions of the components a, b, c, d, e, f, g are coestimated using a least squares procedure. We found the correlation between Nino3.4 and IOD indices and rainfall time series to be maximum when the lag is zero. Therefore, the normalized ENSO $\bar{E}$ and IOD $\bar{I}$ indices without considering any time lags, i.e., $\phi_{ENSO}=\phi_{IOD}=0$ are considered for the rainfall. The estimated coefficients for g and h are summarized in Figure 11. The magnitude of ENSO and IOD over 2003–2013 reached 25 mm whereas the magnitude of the annual ($\sqrt{c^2+d^2}$) and semiannual components ($\sqrt{e^2+f^2}$) were 70 and 50 mm, respectively. The same procedure was repeated for TWS time series while considering a lag of one month for both ENSO and IOD ($\phi_{ENSO}=\phi_{IOD}=1/12$). This selection is due to the fact that a delay of around 1–2 months exists between rainfall changes and TWS changes as was discussed under rainfall variability analysis. The corresponding coefficients are summarized in Figure 12. The magnitude of their contribution reached 15 mm, over the period of 2003–2013. This is relatively less than what we observed for TRMM-rainfall in Figure 11. Considering the simple water balance equation, where the derivative of

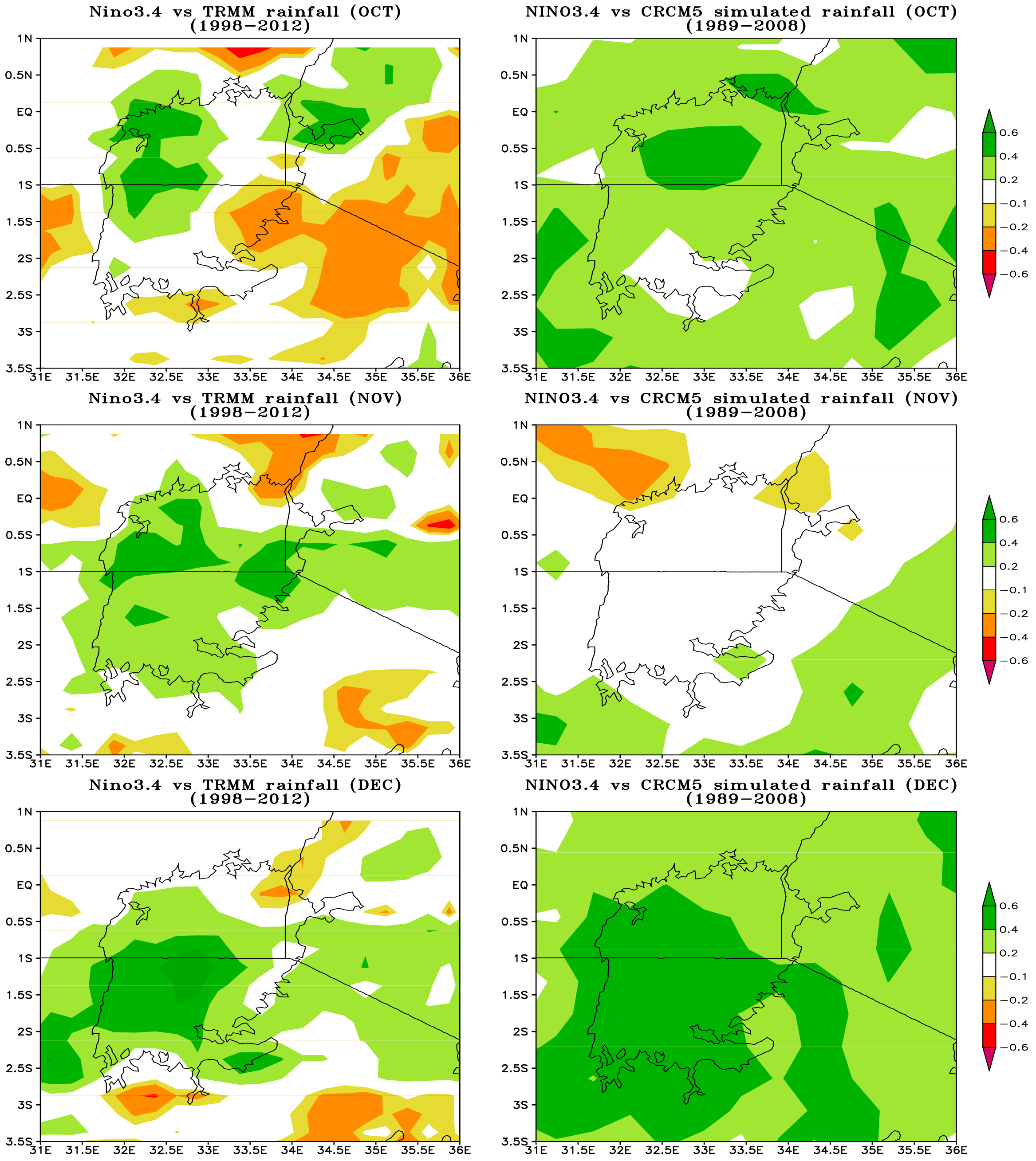

Figure 9. Spatial correlation between ENSO (Nino3.4 index) and monthly rainfall over LVB ($r = 0.44$ significant at 0.05 confidence level). (top) October, (middle) November, and (bottom) December.

TWS is equal to precipitation minus evaporation minus runoff, when a phenomenon like ENSO happens, the amplitude of precipitation increases. One should, however, also consider that consequently, the amplitude of evaporation and runoff will increase and to some extent cancel out a part of the extra input water.

3.5. Economic Implications of Observed and Simulated Covariability of LVB Climate and Total Water Storage

[34] This section provides an overview assessment of the economic impact of climate change linked to changes in stored water potential of Lake Victoria Basin as discussed in section 3. It is important to point out that impact of climatic change on economic activities is systemic, thus quite complex and cannot be reduced to only monetary metrics for a single time period. Invariably, the economic impact of climatic change can be categorized as first-order impact, and second order impact. The first-order impact can be noticed right after a major extreme climatic event occurs, such as drought or floods (e.g., the El Niño rains of 2007, Figure 3). The second-order impacts are linked to climatic variations in the LVB that happens over protracted length of time or erratic happenings such as unpredictable rainy and dry seasons, which do not correspond to, or altogether disrupt planned-economic activities. In addition, lingering

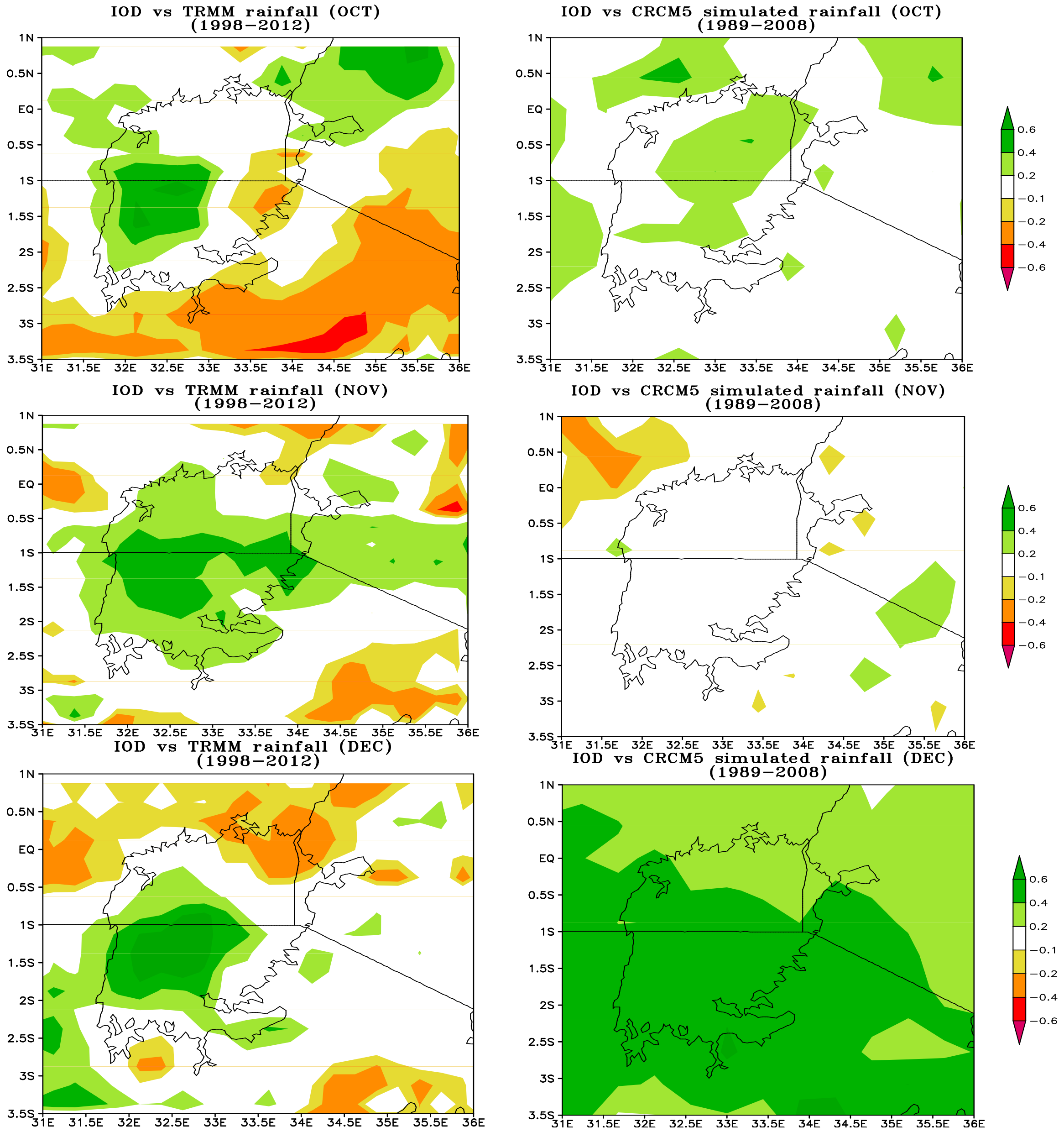

Figure 10. Spatial correlation between IOD (index) and monthly rainfall over LVB ($r = 0.44$ significant at 0.05 confidence level). (top) October, (middle) November, and (bottom) December.

economic effects often happen in an incremental patter over protracted periods of time.

[35] Equally important, is the need to understand the complex link between economic and social variables, which when subjected to climatic change, then engenders negative outcomes, both in the short and long term. At the center of economic impact assessment overview is also the heavy dependence of majority of the LVB population on certain economic activities, and therefore negative impact on such activities due to climatic change must be perceived within this reality. For instance, 80% of the LVB population is engaged in small-scale agricultural production and livestock farming, while fishing directly or indirectly support the livelihood of about 3 million people [*East African Community Secretariat*, 2004; *Ntiba et al.*, 2001; *LVBC*, 2011]. The population of LVB depends on wood biomass for 90% of their energy requirement [*LVBC*, 2007].

[36] It is difficult to arrive at precise monetary figures when making assessment of economic impact of climatic change in the LVB. This is because costs extend well beyond noneconomic sectors in the eco-system, but have indirect negative bearing on economic activities in the LVB. Compounding the difficulty of measuring precise economic impact is the sheer lack of accurate statistical data of the gross domestic product (GDP) of the LVB. Lake Victoria Basin Commission (LVBC) officials give conflicting GDP figures of $30 billion, and 40 billion for 2011 and 2012, respectively in various presentations [see, *Mngube*, 2011; *Kanangire*, 2012]. Knowing the accurate GDP can be helpful in estimating the economic impact of

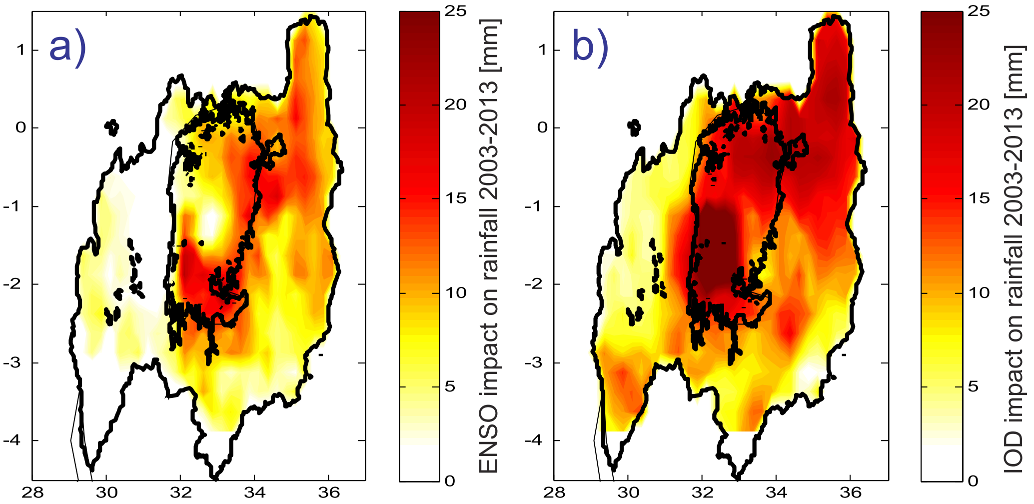

Figure 11. Contribution of (left) ENSO and (right) IOD on the TRMM-derived rainfall variability of LVB.

changes in stored water potential of Lake Victoria due to climate change. We can then know percentage decrease or increase in GDP that may have resulted from such variability. Hence the overview assessment of economic impact given here is restricted to giving the correlating economic impact to distinctive climatic events drought, floods, and erratic seasonal rainfall patterns within spatial dimension.

[37] The major economic sectors that are subjected to first-order impact of climatic change are: water resources, ecosystems and fishery, agriculture, energy, transportation, infrastructure and communications, and public health and labor productivity. The second-order economic impact of climatic change are such as lingering food shortages, energy poverty, malnutrition and impaired learning ability, and gradual loss of ecosystems that previously supported economic and social life of inhabitants. The 1997/1998 El Niño floods (see, Figure 2) caused damage to buildings, roads, communications systems, crops, and in addition to costs of treating diseases [*Mogaka et al.*, 2005]. This type of damage has immediate and lingering future costs. Taking the costs of replacement of infrastructure, we can assess immediate costs for all damaged structures, in addition to lost value due to impaired infrastructure, cost of treating diseases, and lost productivity due to diseases and inability to move and communicate freely.

[38] Likewise, the drought spawned by La Niña between October 1998 and 2000 led to massive crop and livestock loss, decreased hydro-electric power station outputs, water shortage and contamination-related diseases [*Mogaka et al.*, 2005]. *Awange et al.* [2007] found a link between highly variable climate pattern in the LVB to the frequency and severity of droughts and food insecurity in the region or parts of it. A commissioned research by United States Agency for International Development (USAID) conducted by International Resource Groups [*Hecht et al.*, 2011], gives some conservative estimates of cost of climate change for LVB at about $ 6.5 billion for the year 2005, in period in which LVB level dropped [see, Figure 7 and also *Awange et al.*, 2008a]. This study gives the GDP of the LVB at around $ 31.4 billion, thus the cost of climate change impact stands at almost 21% of the region's GDP for the single year. Even more surprising result of this study

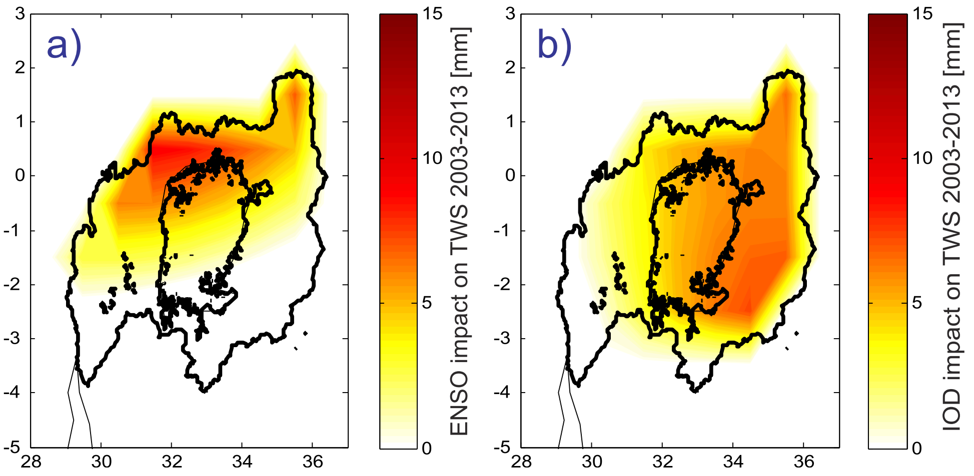

Figure 12. Contribution of (left) ENSO and (right) IOD on the GRACE-derived TWS variability of LVB.

is the huge cost of public healthcare, which claims 4.4% of LVB GDP. Huge costs in healthcare are related to the elevated incident of malaria, diarrheal diseases, and malnutrition, all of which have direct link either to drought or floods [*Wandiga*, 2006]. The economic impact overview assessment here depicts great exposure of the LVB's economic activities to adverse impact of climate change. However, there is need for accurate data from which reliable monetary cost of the impact of climate change can be measured and therefore allowing for cost-effective adaptation mechanisms to be planned and implemented.

4. Conclusions

[39] In this study, decadal water storage changes over the basin derived from monthly GRACE, TRMM, and RCM products are analyzed. The PCA results from both GRACE and TRMM together with in situ data analyzed showed a slight increase in rainfall and water volume over Lake Victoria Basin.

[40] Overall our study confirms that there has been a modest increase in rainfall and stored water over the basin during the last decade. This is captured by in situ observed data obtained from lake-shore stations, TRMM and GRACE satellite remote sensing. TRMM data suggest that rainfall conditions have not changed much during the study period (1998–2013) over the basin while GRACE-TWS indicates average mass decline of 38.2 mm/yr for the period 2003–2007 and increase of 4.5 mm/yr for 2007–2013 over the basin. This decline has been attributed to expansion of the Owen Falls/Nalubale Dam, at Jinja Uganda in earlier investigations by *Awange et al*. [2008a, 2008b] and *Swenson and Wahr* [2009].

[41] Furthermore, the four high-resolution regional climate model simulations analyzed clearly reproduced the broad spatial and temporal patterns of precipitation over the LVB, as well as El Nino and La Nina linked anomalous wet and dry conditions during the recent decades. However, only two (CRCM5 and PRECIS) of the four RCMs capture the observed spatial distribution of rainfall over the LVB, and this is likely to compromise their ability to depict the correct (GRACE) water stored over the LVB.

[42] The economic impact assessment of LVB depicts great exposure of the LVB's economic activities to adverse impact of climate change, specifically its impact on stored water.

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