Lake level change and total water discharge in East Africa Rift Valley from satellite-based observations

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ABSTRACT

The measurement of total basin water discharge is important for understanding the hydrological and climatologic issues related to the water and energy cycles. Climatic extreme events are normal climatic occurrences in Africa. For example, extensive droughts are regular features in the last few decades in parts of East Africa, which suffers from a lack of *in situ* observations as well as a lack of regional hydrological models. In this study, multi-disciplinary different types of space-borne observations and global hydrological models are used to study total water discharge in the Great Rift Valley of East Africa (i.e. Lakes Victoria, Tanganyika, and Malawi) from January 2003 to December 2012. The data include the following: (1) total water storage (TWS) variations from Gravity Recovery and Climate Experiment (GRACE), (2) the lake level variations from Satellite Alimetric data, (3) rainfall from Tropical Rainfall Measurement Mission (TRMM) products, (4) soil moisture from WaterGAP Global Hydrology Model (WGHM), and (5) water fluxes from Global Land Data Assimilation System (GLDAS). Results show that a significant decline in the average lake level is found for all of the three lakes between 2003 and 2006. GRACE TWS variations of the whole basin area show the same pattern of variation as the average lake level variations estimated from Altimetric data. The TWS in the basin area of Lakes Victoria and Malawi is governed by the surface water stored in each lake itself, while for Lake Tanganyika, it is governed by both surface water and the soil moisture content in the basin area. Furthermore, the effect of rainfall on TWS is also studied. A phase lag of ~2 months is found between TRMM rainfall and GRACE TWS (generally, rainfall precedes the GRACE TWS) for the three lakes. In addition, the regional evapotranspiration ET is estimated from the water balance equation using GRACE land–water solutions, rainfall data from TRMM and runoff values obtained as a fraction of rainfall. It is found that the computed ET represents approximately 90% of the rainfall over the study region.

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1. Introduction

The volume variations of water stored within Lakes and reservoirs are the indicator of the combined impact of climate change and water cycle (Jin and Feng, 2013). The overall lake water volume depends on the balance between the water inputs and outputs. The inputs are the sum of direct rainfall over the lake, surface runoff from the drainage basin area, and underground seepage (which can be neglected). The outputs are the sum of direct evaporation from the lake, river outflow, and groundwater seepage. Groundwater seepage is usually a minor component of the water budget and can be neglected or defined as a constant value in the water budget equation (Cretaux and Birkett,

2006). Some of these components can be remotely sensed (e.g. rainfall, lake level), while others can be estimated from global and regional hydrological models (e.g. evapotranspiration).

The great lakes of East African Rift Valley (Fig. 1) are unique natural resources that are heavily utilized by their bordering countries for water supply (for drinking, agriculture, industry, and hydropower production), transportation, fish production, waste disposal, recreation, and tourism. The population density is high and heavily concentrated near the lakes, which are consequently under considerable pressure from a variety of human activities (Cohen et al., 1996). The boundaries of the East African Rift Valley lakes span a range of latitude from 04°35″N to 14°30″S (Spigel and Coulter, 1996), containing large lakes and many smaller freshwater bodies (wetlands and rivers). Lakes Victoria, Tanganyika, and Malawi are the three largest lakes in the East African Rift Valley (Odada et al., 2003). However, monitoring water storage variations in East African Rift Valley lakes is difficult because of the lack of a

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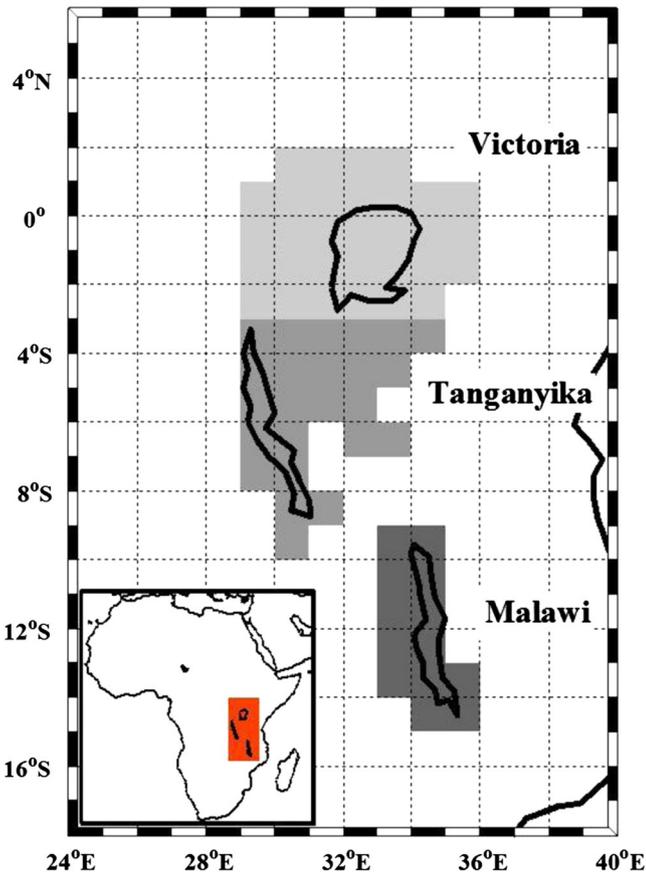E-mail addresses: sgjin@shao.ac.cn, sg.jin@yahoo.com (S. Jin).

Fig. 1. Boundaries of East African Great Lakes from the drainage network provided by the model routing Total Runoff Integrating Pathways (TRIP; Kundzewicz et al., 2004). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

comprehensive global monitoring network with high cost and strong labor intensity.

The satellite gravimetry, particularly the Gravity Recovery and Climate Experiment (GRACE) mission, provides a unique opportunity to detect continental water storage variations (Jin et al., 2010, 2012). GRACE has been widely used for estimating global and regional water storage variations. Awange and Ong'ang'a (2006) investigated the cause of the decline in Lake Victoria level during 2002 to 2006 using satellite estimates of rainfall from TRMM, water storage from GRACE, and tropopause temperatures from CHAMP satellite's radio occultation. Their analysis of GRACE results showed a decrease in geoid heights, which demonstrated that during the study period of the basin losing water, the rainfall was stable, and the temperature did not increase significantly to cause a massive evaporation, leading them to conclude that the major contributor to the lake's decline was dam discharge rather than climatic changes. However, Awange and Ong'ang'a (2006) did not account for all the components of water balance equations. Swenson and Wahr (2009) examined trends in lake level and water storage in the basin area of Lake Victoria from 2003 to 2008 and found that the relative effect of drought and the human management of the lake outflow in lake's decline were of similar size. Becker et al. (2010) analyzed the variability in terrestrial water storage, lake water volume, and rainfall over parts of East Africa from 2002 to 2008 and showed that the interannual variability of total water discharge was due to forcing by the 2006 Indian Ocean Dipole (IOD) on East Africa rainfall. Becker et al. (2010) did not estimate evapotranspiration directly.

In this study, GRACE and satellite altimetric measurements from January 2003 to December 2012 over the East African lakes and their drainage basins are jointly analyzed in order to know the spatiotemporal and multi-scale variations of hydrological conditions in this region. Rainfall data and hydrological models are also further analyzed to infer the effect of rainfall and evapotranspiration on the water storage in this region and to estimate the total discharge using the water balance equation that was not analyzed in previous studies.

2. East African Great Rift Valley

The East African Great Rift Valley has drainage basins of the three great lakes. Fig. 1 shows the boundaries of the basin areas of Lake Victoria, Lake Tanganyika, and Lake Malawi. The boundaries of the drainage basin of each lake are obtained from the Total Runoff Integrating Pathways (TRIP) network (Oki and Sud, 1998). The TRIP network has been prepared at a spatial resolution of $1° × 1°$. The aim of TRIP is to provide information of the direction of flow of water over land.

From limnological perspective, the distinguishing attributes of these are their large size and volume as well as their tropical locations. Lake Victoria is the world's second largest freshwater lake measured by surface area and the eighth largest lake by volume. In addition, it is the largest tropical lake in the world. The lake surface is shared between Kenya (6%), Uganda (43%), and Tanzania (51%), while its basin also includes parts of Burundi and Rwanda (Kizzaa et al., 2012). Much of the Lake is relatively shallow with an average depth of about 40 m, and therefore its volume is substantially less than that of other Eastern African Lakes with much smaller surface area (Awange and Ong'ang'a, 2006). The water balance is dominated mainly by rainfall on the lake, evaporation, and river outflow, with river inflow making a minor contribution (Spigel and Coulter, 1996). Kagera River is the main river flowing into the lake while outflow from the lake contributes most of present-day White Nile River flow. In Uganda, hydropower is the main source of electricity for the country (WWAP, 2006).

Lake Tanganyika is the longest lake in the world with around 673 km along its major axis and the world's second deepest lake after the Lake Baikal. Although it is less than half the size of Lake Victoria, it drains an area approximately of a similar size (200,000 km²). The lake crosses Burundi, Congo, Tanzania, and Zambia. Lake Tanganyika is fed by a number of small rivers and two major rivers: the Rusizi flowing from Lake Kivu to the north and the Malagarasi flowing from Western Tanzania south of the Victoria Basin. Only a single outlet drains Lake Tanganyika, which is the Lukuga River. Most of Tanganyika's water loss is through evaporation (Odada et al., 2003).

Lake Malawi is located in the southern end of the Great Rift Valley region, which is the fourth deepest inland water body in the world. The lake is also an elongated lake surrounded by mountains with highest elevations to the north. The boundaries of the lake cross Malawi, Mozambique, and Tanzania. The only outlet of Lake Malawi is the Shire River at its southern end. Table 1 shows the morphometric data of the three great lakes in the East African Great Rift Valley.

Table 1
Morphometric data for Africa's three largest lakes (Odada et al., 2003; Awange and Ong'ang'a, 2006; Kizzaa et al., 2012).

	Victoria	Tanganyika	Malawi
Location	03° 00″S–00° 20″N 31° 39″E–34° 53″E	08° 48″S–03° 20″S 29° 03″E–31° 12″E	14° 40″S–09° 30″S 33° 50″E–35° 17″E
Catchment area (km²)	194,000	220,000	126,500
Lake area (km²)	68,800	32,600	29,500
Total area (km²)	262,800	252,600	156,000
Lake/catchment ratio	35%	15%	23%

3. Satellite observations and models

3.1. Satellite altimetry

Despite of some limitations, satellite altimetry is of major importance for hydrology science for most lakes in the world since the data are freely available worldwide. Although the primary objective of Radar altimetry is to map oceanic sea surface heights, they can successfully contribute to the measurement of water level variations in lakes and inland seas. The measurements can be acquired along the position of the satellite ground track with accuracy of the order of a few centimeters to tens of centimeters (Cretaux and Birkett, 2006; Cretaux et al., 2011).

The U.S. Department of Agriculture's Foreign Agricultural Service (USDA-FAS), in cooperation with the National Aeronautics and Space Administration, is routinely monitoring water level variation for more than 75 large lakes and reservoirs around the world. The time series of altimetric water level variations for some of the world's large (>100 km^2) lakes and reservoirs are provided by USDA and can be found at http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir. A comparison of altimetric lake levels and stage measurements of Lake Victoria near Jinja, Uganda, during the period 2000–2004 showed excellent agreement (Reynolds, 2005) http://www.fas.usda.gov/pecad/highlights/2005/09/uganda_26sep2005/images/2000_2005.htm. Thus, it is possible to use altimetric lake levels in place of *in situ* stage measurements to estimate the lake level change (Swenson and Wahr, 2009).

3.2. Satellite gravimetry

The Gravity Recovery and Climate Experiment (GRACE) satellite mission, sponsored by NASA and German counterpart DLR, has been collecting gravimetric observations. GRACE is considered as an extremely valuable tool to monitor mass redistribution within the Earth's system with a spatial resolution of ~300 km (half wavelength) and monthly temporal resolution. It can be used to estimate water storage changes over an entire region or basin with higher accuracy at larger spatial scales (Tapley et al., 2004; Wahr et al., 2004). Although it has relatively low spatial and temporal resolutions, GRACE has the advantage that it senses changes in total water storage in all levels, including groundwater as well as surface water (Rodell et al., 2009). TWS variations observed by GRACE include combined contributions of groundwater, soil water, surface water, snow, and ice. The climate of Africa is warm, so snow and ice are uncommon. GRACE results have been used for assessing the effect of climate change on water storage changes in Africa with a number of cases (e.g., Crowley et al., 2006; Klees et al., 2006; Becker et al., 2010).

One of the main products of GRACE solutions is the level 2 time-variable gravity fields (Flechtner, 2007), which are monthly geopotential solutions released in terms of spherical harmonic coefficients. The GRACE level 2 product is provided by a number of institutes. The latest Release-05 (RL05) L2 spherical harmonics coefficients provided by the Centre of Space Research (CSR) of the University of Texas at Austin up to degree and order 60 are used for this study during the period from January 2003 up to December 2012. Bettadpur (2012). concluded that GRACE RL05 is more accurate than previously released GRACE products because of the de-striping procedure applied to the data. Therefore, GRACE RL05 needs less spatial smoothing than earlier products.

3.3. WaterGAP Global Hydrological Model (WGHM)

The WaterGAP Global Hydrology Model (WGHM) provides estimates of water availability in a global scale with the exception of Antarctica and Greenland at a spatial resolution of 0.5° × 0.5° (Döll et al., 2003). The WGHM is driven by monthly 0.5° gridded climate data, which is based on spatially distributed physiographic characteristics such as land cover, soil properties, hydrogeology, and the location and area of reservoirs, lakes, and wetlands (Hunger and Döll, 2008). The model has basically been developed to simulate variations of water storage components within the framework of water availability and water use assessment at the global scale over river basins (Güntner et al., 2007). However, the model has been applied in a number of studies dealing with water scarcity and water stress (Smakhtin et al., 2004; Alcamo et al., 2007) and the impact of climate change on irrigation water requirements as well as on droughts and floods (Döll, 2002; Lehner et al., 2006).

The WGHM accounts for the water storage in the surface water (rivers, lakes, and wetlands), snow, soil water, and groundwater storage. The model does not consider water storage within biomass and ice (including permafrost), which usually have much longer rates of variability (decadal and longer) (Güntner et al., 2007). WGHM is based on the best global data sets currently available and simulates the reduction of river discharge by human water consumption. In order to obtain a reliable estimate of water availability, it is tuned against measured discharge using a number of gauging stations, which represent 50% of the global land area and 70% of the actively discharging area (Döll et al., 2003).

In this study, the latest version of WGHM (Hunger and Döll, 2008) tuned against discharge from 1235 gauging stations is used. The model is forced with the Global Precipitation Climatology Centre (GPCC) Full Data Product for precipitation and data from the ECMWF integrated forecast system. A simple approach for precipitation correction was introduced by Fiedler and Döll (2007). WGHM computes not only the long-term average water resources of a drainage basin but also the water availability indicators that take into account the interannual and seasonal variability of runoff and discharge (Döll et al., 2003).

Although the model is globally available, large areas of the globe still suffer from limited discharge information (e.g. parts of Africa) (Güntner et al., 2007). In Africa, most basins in the north part of the equator do not perform well, while the interannual variability of the Central African Congo and the semi-arid to arid Southern African basins of the Zambezi and Orange are captured (Döll et al., 2003).

3.4. The Global Land Data Assimilation System (GLDAS)

The Global Land Data Assimilation System (GLDAS) project is led by scientists of the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) in association with researchers of the Princeton University, the University of Washington, and the Weather Service Office of Hydrology (Rodell et al., 2004b). GLDAS is a land surface simulation system that aims to ingest satellite- and ground-based observational data products, using advanced land surface modeling and data assimilation techniques, in order to generate optimal fields of land surface state (e.g., soil moisture, snow, and surface temperature) and flux (e.g., evapotranspiration, sensible heat flux) products (Rodell et al., 2004b). Currently, GLDAS drives four land surface models, namely, the Community Land Model (CLM) (CLM2; Dai et al., 2003), Mosaic (Koster and Suarez, 1996), Noah (Ek et al., 2003), and the Variable Infiltration Capacity (VIC) (Liang et al., 1994).

Several studies have used evapotranspiration predicted by the GLDAS to validate results derived from a combined approach of using GRACE and other data sets. Ramillien et al. (2006) estimated the time series of basin-scale regional evapotranspiration rate and associated uncertainties within 16 drainage basins using GRACE land water estimates and independent information on precipitation and runoff. Evapotranspiration results are compared to outputs of four different global land surface models (including WGHM and GLDAS). Comparison of the GRACE-based evapotranspiration with different global LSMs ET estimates shows good overall agreement, especially at the seasonal timescale.

Cesanelli and Guarracino (2011) used the water-balance equation to estimate evapotranspiration using the GRACE land–water solutions, precipitation data, and runoff values over the Salado basin in Argentina. Their computed ET rates with both GRACE and GLDAS are in good agreement with RMS error of 25.0 mm/month (0.83 mm/day), which is in the order of the RMS reported by precedent studies (e.g. Rodell et al., 2004a; Ramillien et al., 2006) when they compared the ET derived from GRACE and GLDAS in different basins over the globe. Rodell et al. (2004a) found an RMS error of 0.83 mm/day over Mississippi River basin. Here, we used four versions (CLM, Mosaic, Noah, and VIC) of the GLDAS version 1 (GLDAS-1) 1.0° resolution to estimate evapotranspiration rates over the study area.

3.5. Rainfall data

Launched in 1997, the Tropical Rainfall Measuring Mission (TRMM) was a joint mission between the National Aeronautics and Space Administration (NASA) of the United States and the National Space Development Agency (NASDA) of Japan. The main objective of TRMM is to measure rainfall of tropical and subtropical regions of the world (Kummerow et al., 1998). TRMM is designed to monitor tropical rainfall in the latitude range ± 50°. The primary rainfall instruments on TRMM are the TRMM Microwave Imager (TMI), which is a nine-channel passive microwave radiometer, the precipitation radar (PR) (the first rain radar in space), and the Visible and Infrared Radiometer System (VIRS), a five-channel imaging spectroradiometer using visible and IR techniques (Kummerow et al., 1998). There are a number of products based on the TRMM observations, whose use is dependent upon the subject of interest. In this study, TRMM-3B43 rainfall rate products available with monthly temporal resolution and 0.25° × 0.25° spatial resolution are used over latitude range ± 50°. This rainfall product employs TRMM observations as well as data from a number of other satellites and ground-based rain gauge data (Huffman et al., 2007).

TRMM observations have been used in several studies of rainfall over Africa. Awange and Ong'ang'a (2006) studied the falling levels of Lake Victoria using a combination of TRMM, GRACE, and CHAMP satellite data. Asadullah et al. (2008) compared five satellite-based rainfall estimation algorithms against historical monthly rainfall statistics from rain gauges within four regions of Uganda directly to the north of Lake Victoria and found that the TRMM 3B43 rainfall rate products show greatest similarity to gauge data across most aspects of rainfall estimation. Dinku et al. (2007) evaluated various satellite-based rainfall products using station networks distributed throughout the Ethiopian highlands to the northeast of the Lake Victoria region and found that TRMM-3B43 rain rates showed a better performance.

4. Methods and data processing

4.1. Estimation of total water storage (TWS) from GRACE

After removing the temporal mean, GRACE observations are corrected for correlated errors by post-processing GRACE monthly solutions with a moving window filtering method according to Swenson and Wahr (2006b). However, the window width used by Swenson and Wahr (2006b) was not provided in the original paper, and Duan et al. (2009) used Swenson and Wahr's result of window width. Decorrelation is done for the spherical harmonics of order $m = 5$ and above, and the window width w depends on m in the following form:

$$w = \max\left(Ae^{-\frac{m}{k}} + 1, 5\right) \tag{1}$$

where the function $\max(x_1, x_2)$ takes the larger one of the two arguments. Swenson and Wahr (2006b) have empirically chosen $A = 30$ and $K = 10$ for the CSR RL02 data they used at the time, evidently based on a trial-and-error procedure. Here the same values of A and K are used. Then the spherical harmonic coefficients are smoothed with
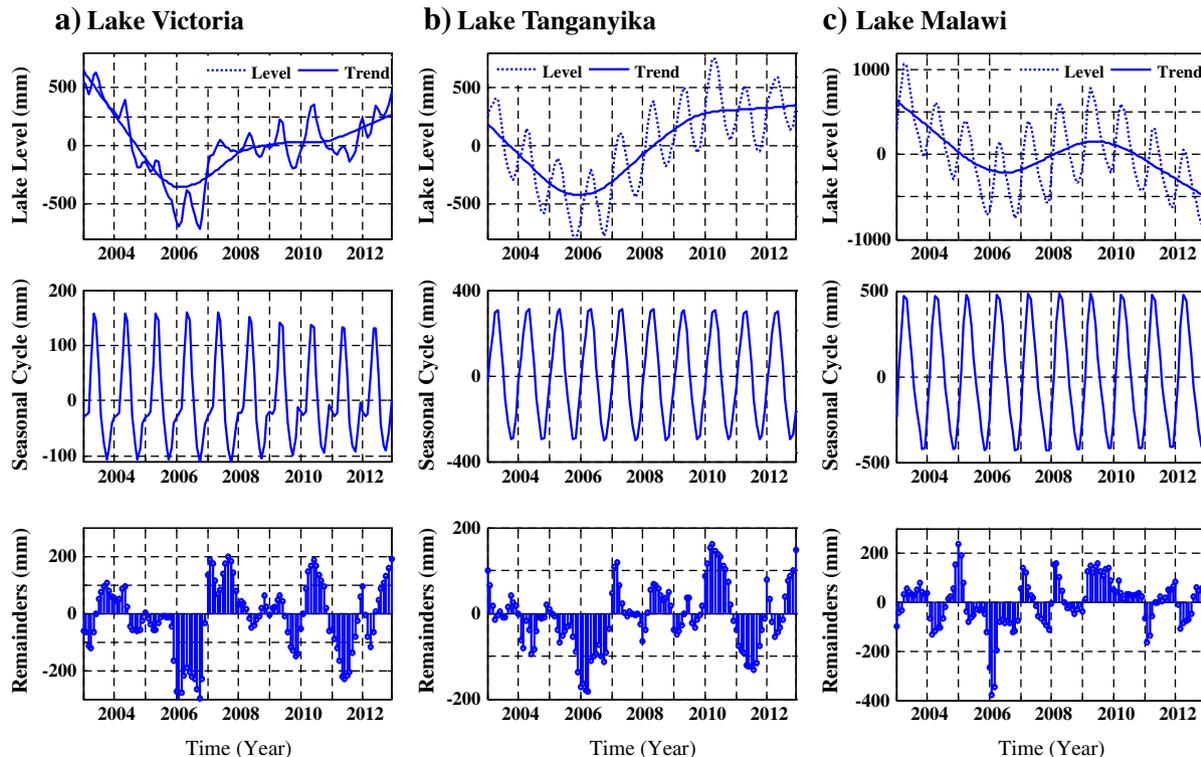

Fig. 2. STL decomposition of the time series of Altimetric lake level. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

a Gaussian averaging kernel of 300 km half width, using the formula represented by Chambers (2006).

Filtering GRACE data has a smoothing effect that reduces the noise as well as the real signal. For that reason, it is usual to apply a scaling factor to GRACE data in order to restore the lost signal. To determine the scaling factor to be applied, a monthly grid of total water storage from WGHM model is extracted over the study area. For each lake, the same filtering procedures are applied to WGHM grids in order to compute the reduction factor compared with unfiltered data. The mean scaling factor obtained for Lake Victoria and Lake Tanganyika is 1.15 and for Lake Malawi is 1.23.

Additionally, the monthly degree 1 coefficients (geocenter) is used from Swenson et al. (2008), and the $C_{2,0}$ coefficients are substituted by measurements from Satellite Laser Ranging (Cheng and Tapley, 2004). GRACE continuously provides monthly mean TWS anomalies; however, in some months, measurement is missing. When data are not available, monthly GRACE solutions of TWS can be linearly interpolated based on values corresponding both to the previous and following months (Ramillien et al. 2006). The time series of GRACE TWS are fitted with five terms: mean, annual sine and cosine, and semi-annual sine and cosine with $t = 0$ at January 1.

4.2. Seasonal-Trend Decomposition Procedure based on Loess (STL)

In this work, the STL method was utilized to model the time series of altimetric lake height as well as the time series of monthly water storage variations from GRACE. The STL method is a filtering procedure that decomposes a time series into additive components of variation (trend, seasonal and the remainder components) by the application of Loess smoothing models (Cleveland et al., 1990).

STL consists of a sequence of smoothing operations each of which, with one exception, employs the same smoother: locally weighted

Table 2
The STL fitted trend of the time series of altimetric lake level and monthly GRACE TWS (in mm/year).

Period	Lake Victoria		Lake Tanganyika		Lake Malawi	
	Altimetry	GRACE	Altimetry	GRACE	Altimetry	GRACE
2003.01–2005.12	−357.82	−41.45	−225.91	−31.29	−289.09	−26.71
2006.01–2008.12	151.44	28.66	203.90	32.10	129.36	26.88
2009.01–2012.12	63.05	5.20	39.66	−2.94	−178.63	−7.76
2006.01–2012.12	79.83	8.69	124.03	7.19	−25.07	6.01
2003.01–2012.12	1.41	2.43	68.62	5.12	−53.12	3.70

regression smoother (LOESS). STL consists of two recursive procedures: outer and inner loops. Each of the passes through the inner loop, which is nested inside an outer loop, consists of a seasonal smoothing followed by trend smoothing that updates the seasonal component and the trend component, respectively. There are six steps in the inner loop: de-trending, cycle-subseries, low-pass filtering of a smoothed cycle-subseries, de-trending of a smoothed cycle-subseries, de-seasonalizing, and trend smoothing. Each pass through the outer loop computes the robustness weight, which can be used in the next run of the inner loop to reduce the influence of transient, aberrant behavior of trend, and seasonal components but is only needed if there are outliers.

STL has several parameters that must be chosen by the data analyst. Mainly, six parameters determine the degree of smoothing in the trend and seasonal components (Cleveland et al., 1990):

- n_p—the number of observations in each seasonal cycle;
- n_i—the number of passes through the inner loop (usually set to equal one or two);
- n_o—the number of robustness iterations of the outer loop (with a value of zero no robustness iteration is applied whilst values of one
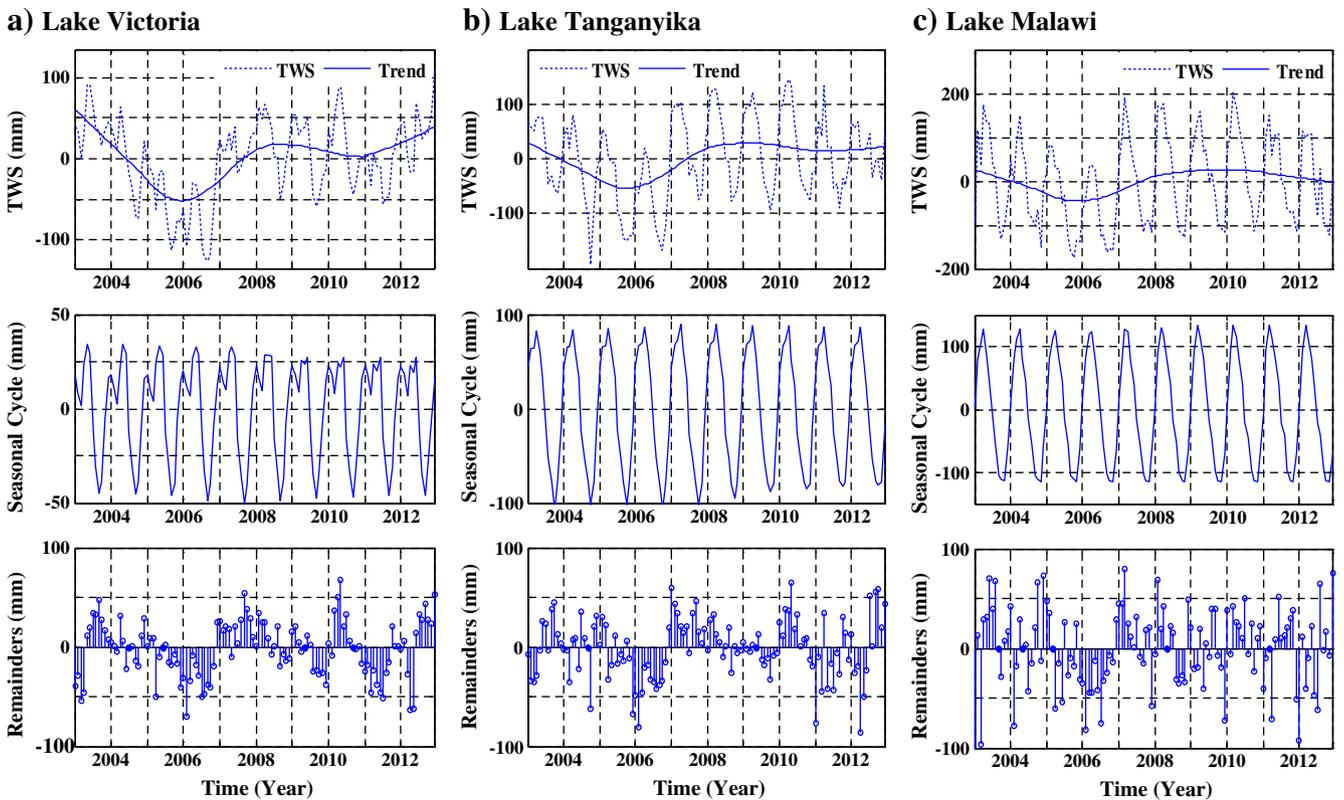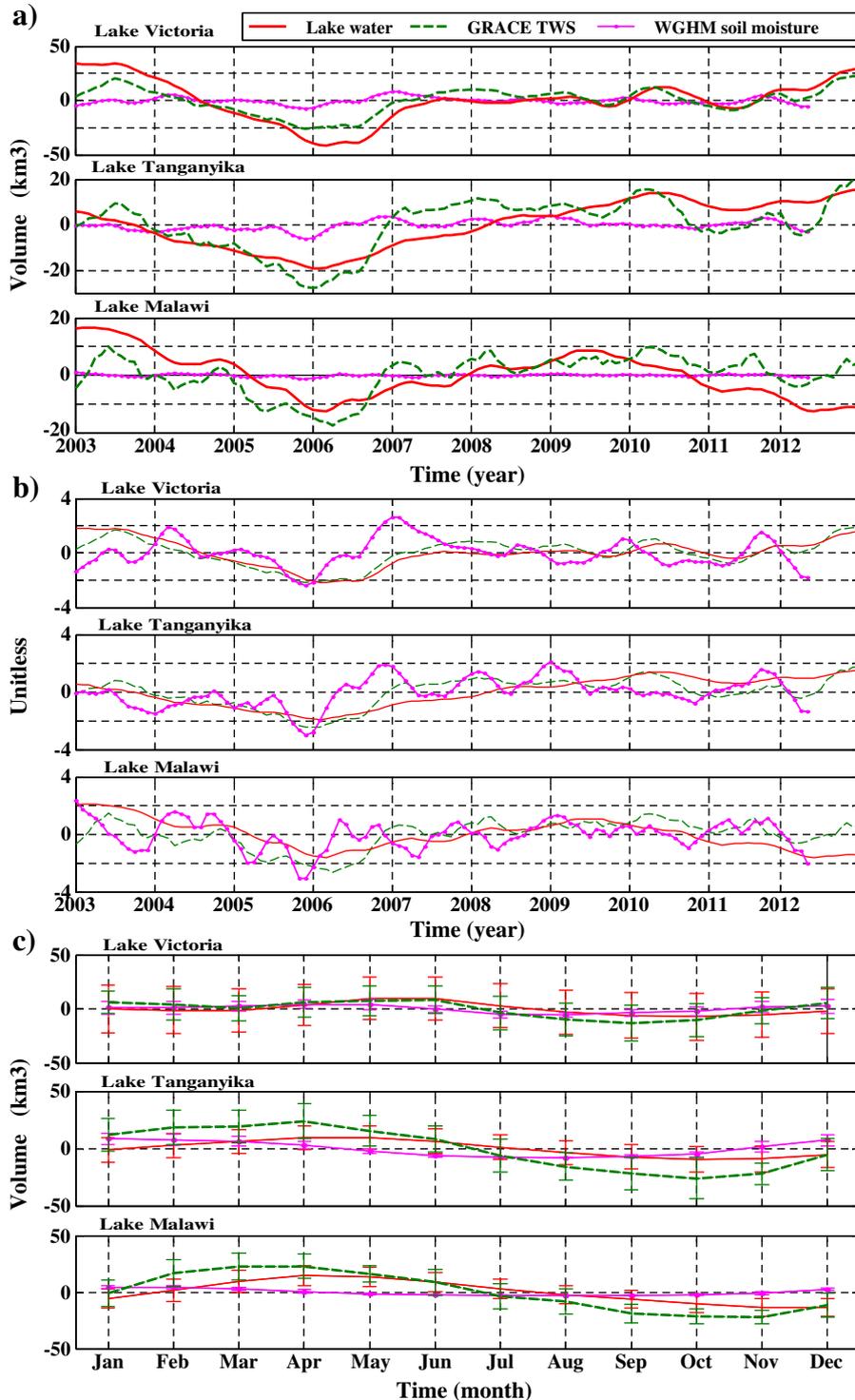

a) Lake Victoria   **b) Lake Tanganyika**   **c) Lake Malawi**

Fig. 3. STL decomposition of the time series of monthly GRACE TWS. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

or more apply increasing robustness, particularly above 5. This parameter is chosen in combination with n_i);

- n_l—the span of the loess window for the low-pass filter (it is recommended to use the next odd number to n_p);
- n_s—the span of loess window for seasonal extraction;
- n_t—the span of loess window for trend extraction. Cleveland et al.

(1990) suggested an empirical formula to compute n_t: $(1.5n_p/(1-1.5n_s^{-1}))$.

Further information on the method and parameters can be found in the original paper describing the STL method (Cleveland et al., 1990).

Fig. 4. Effect of both lake water from Altimetry (red line) and soil moisture from WGHM (magenta line) on GRACE TWS of the basin area (dashed green line). (a) The time series of the three lakes after removing the annual cycle and smoothing with 6-month window. (b) The time series after normalizing all curves to one standard deviation. (c) The seasonal cycle for each lake. The error bars represent the standard deviation for each month. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

5. Results and discussion

5.1. STL decomposition of lake level variations and TWS

Many experiments of using STL method have been conducted with different parameter values. Finally, the parameters in STL of the monthly time series are chosen as follows:

- $n_p = 12$ months (yearly periodicity with monthly data);
- $n_i = 1$ month;
- $n_o = 5$ months;
- $n_l = 13$ months (often computed as the next odd number to n_p);
- $n_s = 12$ months (here we choose the seasonal length to be the same as the periodic length);
- $n_t = 48$ months.

All analyses were performed using the R statistical software environment (R Core Team, 2013). R is a free software programming language and a software environment for statistical computing and graphics. The R language is widely used among statistics and data miners.

We have averaged GRACE-based water storage over each of the three lake drainage basins. Figs. 2 and 3 show the STL decomposition plot of the time series of altimetric lake height and the monthly GRACE TWS, respectively. For each lake, the STL fitted trend is observed in the decomposition plot in comparison with the raw data in the first panel. The STL seasonal and remainder components are shown in the second and third panels, respectively.

In Fig. 2, the STL fitted trend of the time series of altimetric lake height shows a significant decline in the average lake level for all of the three lakes between 2003 and 2006 with different rates as shown in Table 2. The main reason of this significant declination is the drought happened in much of East Africa during this period (Swenson and Wahr, 2009). For Lake Victoria, the lake level declination between 2003 and 2006 is the max among the three lakes with −357.82 mm/year. This is because Lake Victoria is the only one of the three lakes with extensive hydropower development rather than greater atmospheric conditions relative to the regions surrounding Lakes Tanganyika and Malawi (Swenson and Wahr, 2009). After 2006, the lake level started to increase rapidly until 2009 for Lakes Victoria and Malawi and until 2010 for Lake Tanganyika. After that it shows a slight increase for Lakes Victoria and

Table 3
Average annual values of rainfall (from TRMM), runoff (from GLDAS-Noah), and ET (computed from water balance equation). Units are in mm/month.

	P			$R_{surface + subsurface}$			$ET_{Computed}$		
	Vic	Tang	Mal	Vic	Tang	Mal	Vic	Tang	Mal
2003	101.95	80.69	96.64	9.32	3.67	15.11	91.01	74.70	68.66
2004	108.40	96.12	110.38	6.11	6.64	17.69	100.43	86.33	91.63
2005	97.86	68.54	76.12	3.80	6.71	12.92	99.28	73.77	81.34
2006	127.25	113.88	107.39	4.95	2.56	7.47	105.20	88.61	82.78
2007	114.89	91.88	98.37	13.75	8.07	15.76	101.12	77.38	91.56
2008	110.42	95.83	96.94	12.14	13.67	13.74	100.89	86.29	68.44
2009	96.74	90.84	104.63	8.83	19.37	19.07	90.90	81.43	105.03
2010	101.45	80.53	91.70	17.15	16.38	12.85	89.90	74.28	67.46
2011	111.57	106.54	102.29	15.62	13.94	13.65	96.77	93.74	98.83
2012	106.20	84.31	92.06	13.27	8.18	8.43	87.72	68.26	64.60

Tanganyika, while it shows a significant decrease between 2010 and 2012 with −215 mm/year for Lake Malawi.

For each lake, the STL decomposition plot of the monthly GRACE TWS in Fig. 3 shows the same pattern as the time series of altimetric lake height. It shows a significant decrease in the TWS between 2003 and 2006 with the max rate in Lake Victoria, followed by a significant increase until 2009. After that it shows a slight increase for Lake Victoria while Lakes Tanganyika and Malawi experienced a reduction between 2010 and 2012.

The STL seasonal component of the time series of altimetric lake height and GRACE TWS suggests an average annual increase in May for Lake Victoria and a main annual drop exists in October. This follows the bimodal rainfall regime over Lake Victoria region, which includes long rains during March–May (MAM wet season) and short rains during October–December rainfall period with a notable phase lag (which will be discussed in Section 5.3) (e.g. Kizzaa et al., 2012; Lott et al., 2013). For Lakes Tanganyika and Malawi, the annual increase occurs in April while a main annual drop exists in October for Lake Tanganyika and in November for Lake Malawi. Inflow to lakes Tanganyika and Malawi increases through summer (December to April) as a respond to the summer rainfall, which is the main recharge system for these lakes (Jury and Gwazantini, 2002). The lakes' levels and TWS, therefore, follow the seasonal pattern of rainfall cycle.
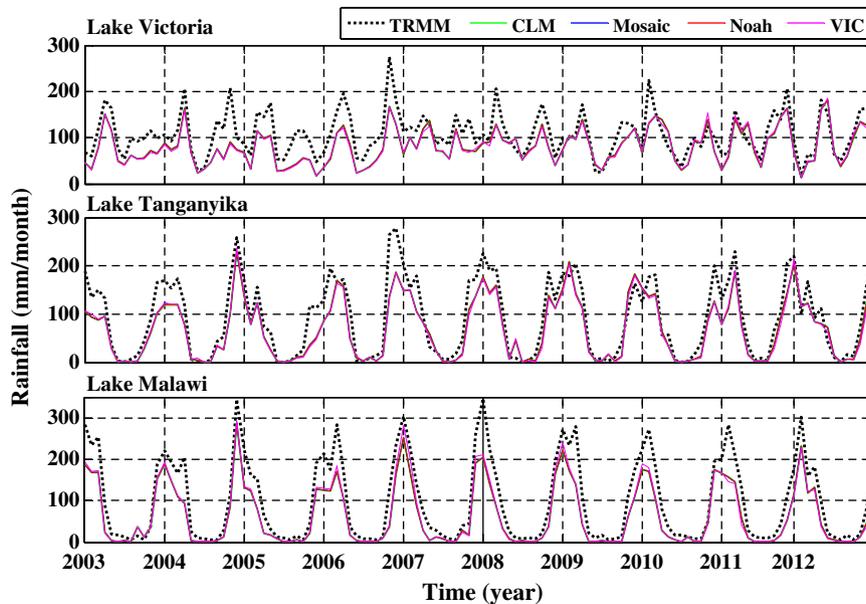

Fig. 5. TRMM rainfall (dotted line) and rainfall rates estimated from GLDAS models (CLM in green, Mosaic in blue, Noah in red, and VIC in magenta). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

Only Lake Victoria shows significant semi-annual variation, which is more obvious in GRACE TWS. In addition, it shows variation across years, with the seasonality being less marked over the last two seasonal cycles. The seasonal cycle of Lake Malawi is the largest, which means that it has faster water renewal than others. In the STL remainder component of the time series of altimetric lake height, the longest vertical lines in 2006 appear as outliers for the three lakes.

5.2. Impact of soil moisture content to TWS

TWS generally contains all phases of water storage above and below the surface of the Earth. Our analysis of storage is limited to soil moisture, groundwater, and surface water. Canopy water storage is negligible in comparison with other components. Also, snow is not taken into account because it is not common in Africa. Comparison between total water storage TWS from GRACE within the whole area of each lake (containing lake area and basin area) and surface water volume change from altimetry in each lake itself is conducted.

Rodell and Famiglietti (2001) concluded that the GRACE can detect changes in water storage within a 200,000 km^2 or larger area. For Lake Victoria and Lake Tanganyika, the drainage basin areas are 262,800 and 252,600 km^2, respectively (Table 1). However, Lake Malawi basin area is considerably smaller, with areas of 156,000 km^2 (Table 1). On the other hand, Becker et al. (2010) suggested that latest GRACE products have improved precision and resolution and allow studying smaller basins. We have averaged GRACE-based water storage and WGHM estimates over each of the three lake drainage basins. In order to *simply* compute the basin water volume (in km^3) for each month, GRACE equivalent water height and WGHM estimates are spatially averaged over the area included inside the basin (Table 1) then multiplied by the basin area. In a similar way, the lake water volume (in km^3) for each month is computed by multiplying the spatially averaged water level over the lake area by the lake area given in Table 1. The annual signal is removed and data are smoothed with a 6-month window.

Because of GRACE low spatial resolution, TWS from GRACE data is contaminated by water mass signals from surrounding areas that may leak into the study region, and thus polluting the estimated TWS. Ramillien et al. (2008) estimated the leakage error and found that the error was of the order of 3.5% of the annual signal over the whole study region. Therefore, it is considered to be negligible on interannual scale.

Fig. 4 shows the time series of the lake water volume (from Altimetry) for each lake in comparison with the basin water volume (from GRACE). Both show a good agreement for the three lakes with correlation coefficients of 86% for Lakes Victoria and Tanganyika and 74% for Lake Malawi. This means that the volume of water in the basin area is governed by the surface water of the lake. In addition, the seasonal cycle (shown in the bottom panel of Fig. 4) shows a good agreement in terms of amplitude and phase for the three lakes. Fig. 4b) shows all the curves after being normalized to one standard deviation to make the comparison easier.

Fig. 4 also shows the time series of the soil moisture volume change as estimated from WGHM outputs. It shows a weaker agreement with the basin water volume (from GRACE) with correlation coefficients less than 50% for Lakes Victoria and Malawi (26% and 31%, respectively) and a correlation coefficient of 51% for Lake Tanganyika.

Table 5
Bias and RMSE of rainfall estimates from the four GLDAS models and TRMM rainfall estimations (in mm/month).

GLDAS model	Lake Victoria		Lake Tanganyika		Lake Malawi	
	Bias	RMSE	Bias	RMSE	Bias	RMSE
CLM	26.48	37.27	22.13	36.28	35.69	49.26
Mosaic	26.47	37.27	22.10	36.32	35.68	49.25
Noah	26.47	37.27	22.13	36.28	35.69	49.26
VIC	27.35	38.59	23.56	37.41	34.15	47.45

From these values, it can be concluded that the volume of water stored in the basin areas of Lakes Victoria and Malawi is mainly governed by surface water of the lake itself, while for Lake Tanganyika, it is governed by both surface water of the lake as well as the soil moisture content. One reason is the percentage of the lake area to the basin area for Lake Tanganyika (~13%), which is smaller than the other two lakes (Lake Victoria 26% and Lake Malawi 19%).

5.3. Impact of rainfall to TWS

In this section, the impact of rainfall rates estimated from TRMM model to the GRACE TWS over the study region is investigated. The time series of rainfall rates from TRMM model for Lakes Victoria, Tanganyika, and Malawi are shown in Fig. 5. The seasonal pattern of rainfall with increasing values occurred mainly during the wet season (March–May MAM) over the study region. The highest rainfall value for a single month is observed in November and December 2006 for Lakes Victoria and Tanganyika with values of ~274 and ~277 mm/month, respectively, while it is observed in January 2008 for Lake Malawi with a value of ~346 mm/month. The average annual values of rainfall are presented in Table 3. It shows that the maximum average annual values occurred in 2006 with values greater that 100 mm/month (except for Lake Malawi, which has a maximum average annual value in 2004). The minimal average annual values occurred in 2005.

Fig. 5 also shows the estimated rainfall from the four GLDAS models in comparison with the TRMM estimated rainfall. For each lake, the estimated rainfall of the GLDAS models (CLM, Mosaic, Noah, and VIC) has similar fluctuations. They almost coincide with each other. Seasonal amplitudes and phases of GRACE TWS and TRMM rainfall from January 2003 to December 2012 are nearly close to each other (Table 4). They also show slight differences from TRMM estimated rainfall. The estimated rainfall of the GLDAS models has a negative bias from TRMM estimated rainfall of ~−26.5 mm/month for CLM, Mosaic, and Noah models and of −27.35 mm/month for VIC model, for Lake Victoria, with an RMS error of ~−37.27 mm/month for CLM, Mosaic, and Noah models and of −38.6 mm/month for VIC model. Table 5 shows the values of bias and RMSE for the three lakes.

Fig. 6a) shows a comparison between the time series of the monthly estimated TRMM rainfall and the change in GRACE TWS. Both curves show, in general, good agreement in most of the study period. Both show increasing trend in late 2005 and 2006. A week agreement is observed in 2009 and early 2010 in case of Lakes Tanganyika and Malawi. Fig. 6b) shows a comparison between the seasonal cycle of the monthly estimated TRMM rainfall and the GRACE estimated TWS. It is clear that TRMM rainfall precedes the GRACE TWS by a phase

Table 4
Seasonal amplitudes and phases of GRACE TWS and TRMM rainfall from January 2003 to December 2012.

Lake	Annual amplitude (mm/month)		Annual phase (months)		Semi-annual amplitude (mm/month)		Semi-annual phase (months)	
	GRACE	TRMM	GRACE	TRMM	GRACE	TRMM	GRACE	TRMM
Victoria	28.32	18.17	−0.17	1.95	19.48	40.73	3.22	−5.07
Tanganyika	85.95	98.62	−0.50	1.75	9.68	5.92	0.48	4.76
Malawi	119.55	125.88	−0.88	1.45	16.45	37.68	−2.25	0.26

shift. The phase lag between the time series can be verified in Table 4 in both annual and semi-annual time scales. In case of annual time scale, the phase lag is about 2.1, 2.25, and 2.3 months for Lakes Victoria, Tanganyika, and Malawi, respectively.

5.4. Estimation of evapotranspiration (ET) using water balance equation

In case of available observed streamflow data, evapotranspiration (ET) can be estimated from the water balance equation in order to assess the relative quality of estimated ET (e.g. Ferreira et al., 2013; Xue et al., 2013). The traditional water balance for a closed basin area is as follows (e.g. Rodell et al., 2004a; Swenson and Wahr, 2006a):

$$\frac{\partial S}{\partial t} = P(t) - R(t) - ET(t) \tag{2}$$

where t is the time, S is the water storage inferred by GRACE, and P, R,

and ET are water fluxes representing precipitation, runoff, and evapotranspiration, respectively.

Because of the lack of *in situ* observations required to quantify the runoff in the study region, long-term water budgets show that runoff represents only a small fraction of the mean annual rainfall (Sala et al., 1982; Varni and Usunoff, 1999; Cesanelli and Guarracino, 2011; Cho et al., 2011). Therefore, the following linear model is used to compute R (Kadioglu and Sen, 2001):

$$R_i = k_R * P_i \tag{3}$$

where R_i and P_i is the runoff and precipitation, respectively, during the month i, and k is a coefficient ranging from 0 to 1.

In order to approximately estimate the suitable value of k for the area under investigation, the GLDAS-Noah grids of surface as well as subsurface runoff are considered over the period of study. The average annual values of R are computed using these data. Table 3 shows the
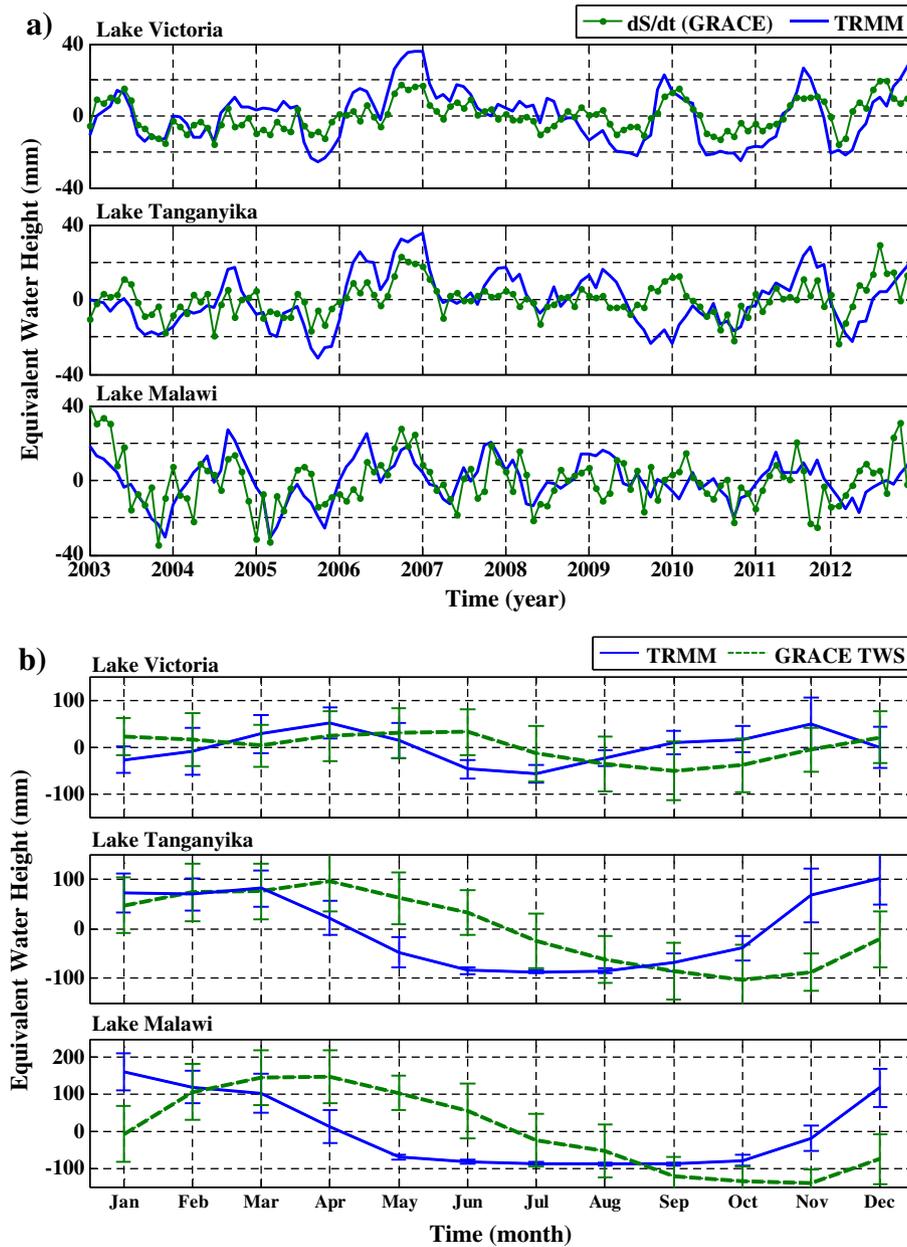

Fig. 6. (a) Monthly estimated TRMM rainfall (blue line) in comparison with the change GRACE TWS (green dashed line). Annual cycle are removed and data are smoothed with 6-month window. (b) A comparison of the seasonal cycles of the monthly estimated TRMM rainfall (blue line) and GRACE TWS (green dashed line). The error bars represent the standard deviation for each month. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

average annual values of R (estimated from GLDAS-Noah model) as well as P (estimated from TRMM model). The average percentage of the model-derived runoff is about 9.8%, 11%, and 14% of the annual rainfall during the study period for Lakes Victoria, Tanganyika, and Malawi, respectively. Temporal variations of k_R are not considered since they may introduce minimal changes in the monthly water balance (Cesanelli and Guarracino 2011). From Eqs. (2) and (3), regional ET can be computed using the following expressions:

$$ET_i = P_i(1 - k_R) - \Delta S_i \tag{4}$$

$$\Delta S_i = S(t_{i+1}) - S(t_i) \tag{5}$$

where ΔS is the change in water storage inferred by GRACE between two months $i + 1, i$.

The time series of computed ET are shown in Fig. 7, and the average annual estimates are presented in Table 3. Fig. 7 shows a seasonal variation of ET with increasing values during the wet season (MAM) for Lake Victoria and during the summer (December–January DJF) for Lakes Tanganyika and Malawi. During the winter (June–August, JJA), which is the dry season in the study region, the ET shows minimum rates with average values less than 60 mm/month for Lake Victoria and less than 10 mm/month for Lakes Tanganyika and Malawi.

From Table 3, it is clear that the maximum average annual ET values occur in 2006, 2011, and 2009 for Lakes Victoria, Tanganyika, and Malawi, respectively, while the minimum values occur in 2012 for the three lakes. A comparison between the time series of the computed ET and rainfall shows that ET represents approximately 90% of the rainfall for the study region.

6. Summary and Conclusion

In this study, we assessed the monthly total discharge of the great lakes in East African Rift Valley (namely, Lakes Victoria, Tanganyika, and Malawi) from January 2003 to December 2012 using GRACE measurements, altimetric data, rainfall data (TRMM model), and hydrological models (WGHM and GLDAS). A significant decline in the average lake level is found for all of the three lakes between 2003 and 2006, with a significant decrease in GRACE TWS for the same period. This is because of the significant drought that happened in much of East Africa during this period. For the whole period of study, GRACE TWS variations of the whole basin area show the same pattern of variation as the average lake level variations estimated from Altimetric data. We further compared GRACE TWS over the whole basin area of each lake with the soil moisture content change estimated from WGHM model. We found that the agreement in case of Lake Tanganyika is better than the other two lakes with 51% correlation coefficient, while a weaker agreement is shown for Lakes Victoria and Malawi. This means that the total discharge in Lake Tanganyika basin area is dominated by both surface water of the lake itself as well as soil moisture content, while for Lakes Victoria and Malawi, it is dominated mainly by the surface water of the lakes.

Monthly rainfall variations over the basin area of each lake are estimated from TRMM model. Results show that rainfall, in general, dominates TWS change in the study region. Rainfall estimates show a seasonal behavior with increasing rates observed mainly during MAM (the wet season) and maximum average annual values occurring in 2006. It is also found that the rainfall variations precede the GRACE TWS by ~2 months phase lag for the three lakes. Rainfall rates are further estimated from the four GLDAS land surface models (CLM, Mosaic, Noah, and VIC). Rainfall estimates from the four models have similar fluctuations and a negative bias from TRMM rainfall estimates. This means that GLDAS rainfall has a dry bias over East Africa region.

Then water balance equations are used to compute regional ET using GRACE TWS estimates, rainfall data from TRMM, and runoff values obtained as a fraction of rainfall. This fraction is estimated in this study by considering surface and subsurface runoff from GLDAS-Noah model over the study period. It is found that this fraction is approximately 9.8%, 11%, and 14% for Lakes Victoria, Tanganyika, and Malawi, respectively. Computed ET shows a seasonal pattern with increasing values occurring during the wet season and summer while it shows minimum rates in the winter (dry season). Moreover, the computed ET is found to represent approximately 90% of the rainfall over the study region.
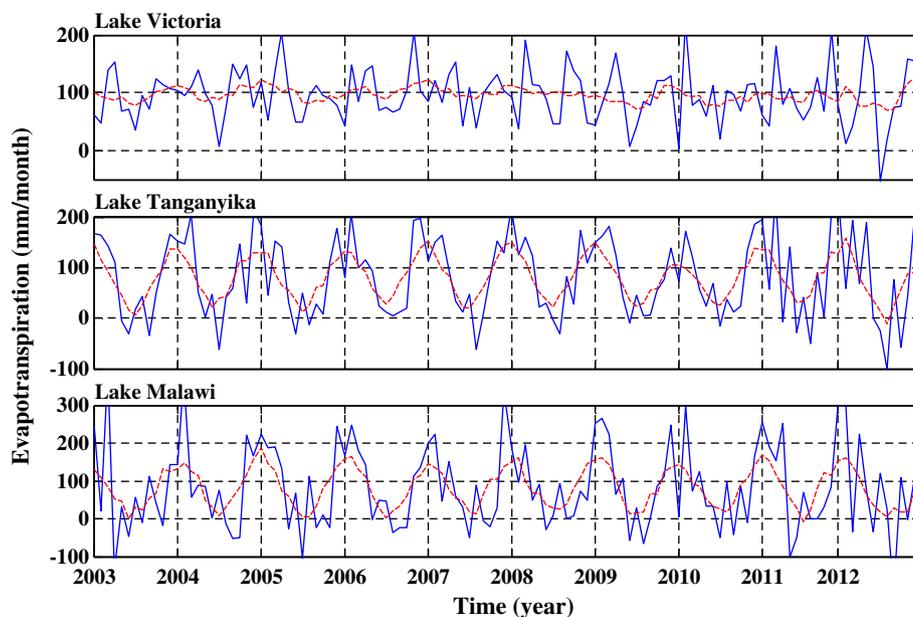
Fig. 7. Time series of ET as computed from water balance equation (solid blue lines) and residuals after smoothing with 6-months averaging window (red dashed lines). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

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