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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.

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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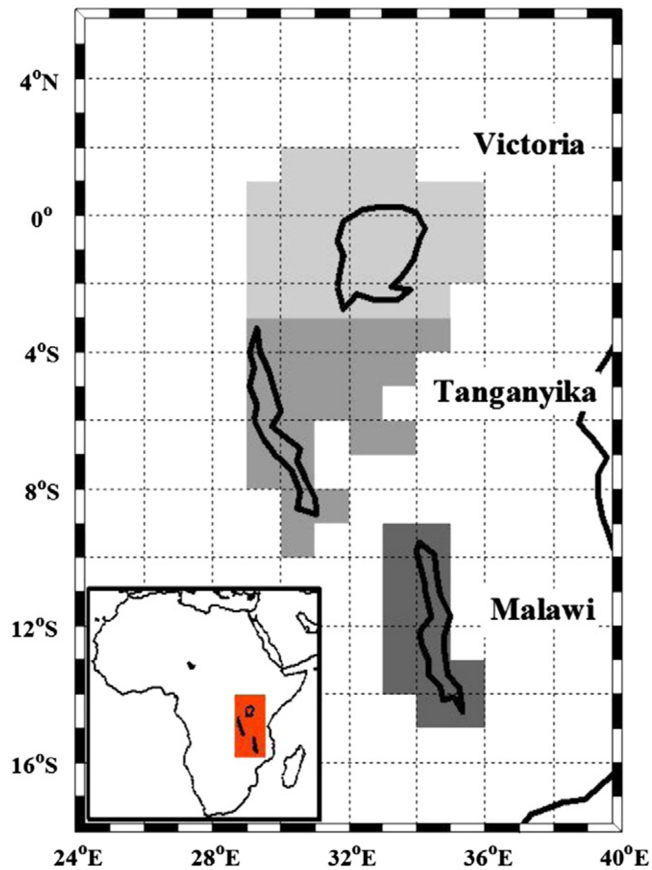

Fig. 1. Boundaries of East African Great Lakes from the drainage network provided by the model routing Total Runoff Integrating Pathways (TRIP; Kundzewicz et al., 2004).

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 $1° \times 1°$. 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 km^2). 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 (km^2)	194,000	220,000	126,500
Lake area (km^2)	68,800	32,600	29,500
Total area (km^2)	262,800	252,600	156,000
Lake/catchment ratio	35%	15%	23%