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Monitoring the water balance of Lake Victoria, East Africa, from space

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SUMMARY

Using satellite gravimetric and altimetric data, we examine trends in water storage and lake levels of multiple lakes in the Great Rift Valley region of East Africa for the years 2003–2008. GRACE total water storage estimates reveal that water storage declined in much of East Africa, by as much as 60 $\frac{\text{mm}}{\text{year}}$, while altimetric data show that lake levels in some large lakes dropped by as much as 1–2 m. The largest declines occurred in Lake Victoria, the Earth's second largest freshwater body. Because the discharge from the outlet of Lake Victoria is used to generate hydroelectric power, the role of human management in the lake's decline has been questioned. By comparing catchment water storage trends to lake level trends, we confirm that climatic forcing explains only about 50decline. This analysis provides an independent means of assessing the relative impacts of climate and human management on the water balance of Lake Victoria that does not depend on observations of dam discharge, which may not be publically available. In the second part of the study, the individual components of the lake water balance are estimated. Satellite estimates of changes in lake level, precipitation, and evaporation are used with observed lake discharge to develop a parameterization for estimating subsurface inflows due to changes in groundwater storage estimated from satellite gravimetry. At seasonal timescales, this approach provides closure to Lake Victoria's water balance to within 17 $\frac{\text{mm}}{\text{month}}$. The third part of this study uses the water balance of a downstream water body, Lake Kyoga, to estimate the outflow from Lake Victoria remotely. Because Lake Kyoga is roughly 20 times smaller in area than Lake Victoria, its water balance is strongly influenced by inflow from Lake Victoria. Lake Kyoga has been shown to act as a linear reservoir, where its outflow is proportional to the height of the lake. This model can be used with satellite altimetric lake levels to estimate a time series of Lake Victoria discharge with an rms error of about 134 $\frac{\text{m}^3}{\text{s}}$.

Introduction

Some thirty million people in the countries of Uganda, Kenya, and Tanzania make their homes in the region surrounding Lake Victoria, shown in Fig. 1. It is the second largest freshwater lake in the world, having an area of approximately 68, 600 km^2. The lake is important economically both locally (for fresh water, aquiculture, agriculture, transportation, and tourism) and further downstream due to its contribution to the flow of the Nile River (Awange and Ong'ang'a, 2006). In Uganda, where the lake's only outflow resides, hydropower is the main source of electricity for the country (WWAP, 2006). Lake Victoria's water balance is therefore controlled both by climatic conditions (via net precipitation and catchment inflow) and human management (via dam outflow) (Yin and Nicholson, 1998).

Since 1959 the outflow of Lake Victoria has been controlled by the Nalubaale Dam located at Jinja, Uganda (Kull, 2006). For most of the following 40 year period, lake levels were above average (Reynolds, 2005). In 1999, a second hydropower facility, the Kiira Dam, was completed, and from that time until the end of 2006, lake levels dropped over 2 m (Riebeek, 2006). During the same time period, much of East Africa experienced significant drought. Because outflow measurements were withheld from the public, speculation grew regarding the relative contributions of managed outflow and decreased net precipitation to the lake's decreasing levels. Kull (2006) simulated the lake water balance for various degrees of drought, and attributed about 45% of the lake level drop to decreased net precipitation and about 55% of the drop to discharge in excess of the "Agreed Curve". The "Agreed Curve", part of a treaty between Uganda and Egypt, specifies the amount of discharge as a function of lake level (Sutcliffe and Petersen, 2007). Its purpose is to reproduce the lake's natural response to climatic conditions, i.e. to mimic the outflows that occurred prior to the construction of Nalubaale Dam in 1959. Sutcliffe and Petersen (2007) constructed an estimate of the lake's level and discharge for the period 2000–2006 based on the assumption that the

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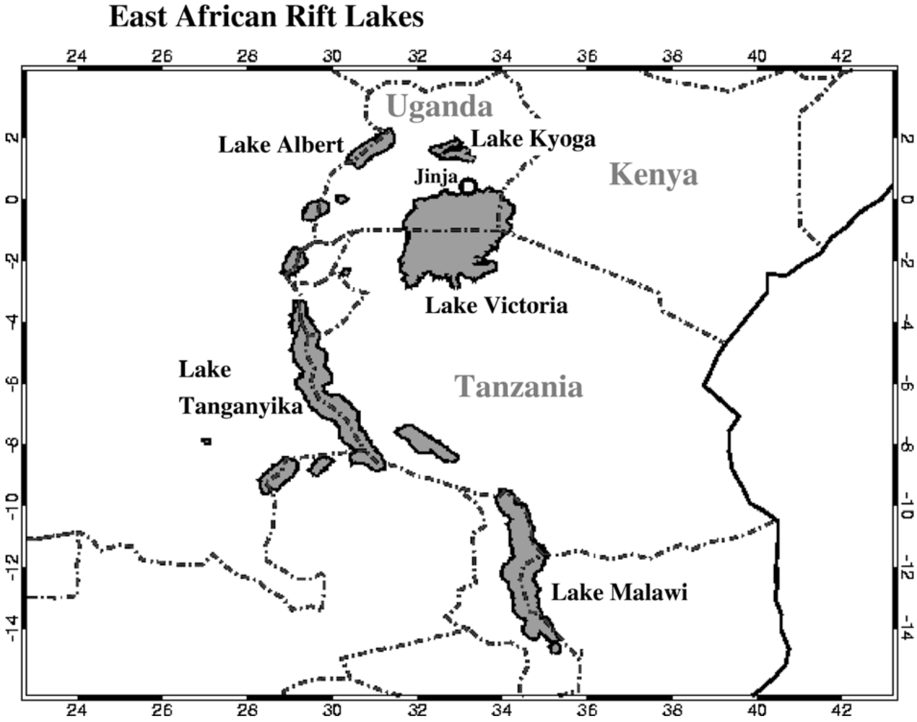

Fig. 1. The Rift Lake region of East Africa. Dashed lines indicate national borders.

outflows were consistent with the "Agreed Curve". From this corrected time series of lake levels, they concluded that of the total water lost from the lake during that period, roughly 50% was caused by over-release.

Recently, measured estimates of discharge from the lake have become available for the period 1950–2005. These measurements (PPA, 2007, (Figs. b-17 and b-18)); indicate that since the middle of the year 2000, lake outflow exceeded that specified by the "Agreed Curve" by 20–30%. As lake levels drop, the discharge calculated from the "Agreed Curve" drops proportionately. The actual dam releases, however, remained relatively stable, with increases in 2003 and 2004 offset by a decrease in 2005. By the end of 2003, the outflow was 150% of the "Agreed Curve", and by the end of 2005 over 200%, confirming the analyses of Kull (2006) and Sutcliffe and Petersen (2007).

The purpose of this study is to apply state of the art satellite remote sensing data to monitor the water balance of Lake Victoria and the surrounding region. Because the health of the lake affects so many people, the ability to routinely observe the lake and make those observations publically available is important. *In situ* observations of the water budget are sparse, and may not adequately represent lake- or basin-averaged values. For example, Yin and Nicholson (1998) noted that lake precipitation was typically 25% greater than that measured in the surrounding catchment, such that even near-shore rain gages failed to provide accurate rainfall estimates for the lake. Dam releases, as noted above, have not always been publically available. Other components of the water balance, such as evaporation and groundwater inflow, are not measured *in situ* at all.

Satellite remote sensing offers a complement to local measurements by providing observations that are temporally and spatially homogeneous. Regionally averaged quantities can be estimated without the under-sampling problem inherent in sparse observation networks. Furthermore, the satellite products used here are free and publicly available. In this study, we use a variety of remotely sensed data products to quantify the water budget of Lake Victoria, and to compare components of its water budget with other water bodies in its vicinity.

It builds upon studies such as Yin and Nicholson (1998), which was based mainly on lake height, precipitation, surface inflow data from a small number of ground stations during the period 1956–1978, by employing recent satellite observations. This study also uses satellite estimates of monthly evaporation and subsurface inflow, two components of the water balance for which Yin and Nicholson (1998) had no observations. More recently, Awange et al. (2007) applied satellite estimates of precipitation, water storage, and tropopause temperatures in an attempt to establish the cause of the decline in lake levels. Their analysis of geopotential data showed a decrease in geoid heights consistent with the drop in lake level observed both *in situ* and by altimetric measurements. Awange et al. (2007) noted that precipitation and tropopause temperatures were stable during the period, leading them to conclude that the major contributor to the lake's decline was dam discharge rather than climatic changes. However, Awange et al. (2007) did not quantify all the components of the Lake Victoria water balance, nor did they estimate evaporation directly.

Three methods for applying remotely sensed data to quantify aspects of Lake Victoria's water balance are described in the sections that follow. The first uses gravimetric water storage and altimetric lake height estimates to separate the mass variability of a lake from its surrounding basin. Two relatively unmanaged lakes are used to examine the relationship between changes in lake levels and groundwater storage in the surrounding watershed. This relationship is then applied to Lake Victoria to estimate the expected change in lake level based on the observed watershed water storage trend. The second approach attempts to quantify the lake water budget using multiple satellite datasets, either directly or indirectly via simple parameterizations. When *in situ* observations of dam discharge are used, the water balance closes to within about 50 $\frac{\text{mm}}{\text{month}}$ at the monthly timescale, and 10—20 $\frac{\text{mm}}{\text{month}}$ at the seasonal timescale. Dam discharge is perhaps the most important component to observe because it is the means by which humans directly influence the lake's water balance. To fulfill this need, we describe an alternate method to estimate remotely the outflow from Lake Victoria by monitoring the water balance of smaller, downstream lakes.

Data

Altimetric lake height

USDA global reservoir database

Lake heights are obtained from the NASA/CNES Topex/Poseidon and Jason-1 satellite missions (Birkett, 1995) via the USDA Global Reservoir and Lake Monitor project. Although the primary focus of these altimeters is to map oceanic sea surface heights, they have also been used to detect water level changes in lakes and inland seas (Cretaux and Birkett, 2006; Birkett et al., 1999; Cazenave et al., 1997). The US Department of Agriculture's Foreign Agricultural Service uses Jason-1 data to routinely monitor height variations of approximately 100 large lake and reservoirs globally. Time series of altimetric lake level variations from the USDA Reservoir Database may be obtained from: http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir.

Validation of satellite altimeter data over inland water bodies is typically performed by comparing altimetric time series and *in situ* stage measurements. The accuracy of elevation variations derived from the Topex/Poseidon mission has been estimated at 3–4 cm RMS for the largest lakes (Shum et al., 2003; Birkett, 1995). 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 amount of lake discharge specified by the "Agreed Curve".

LEGOS/GOHS

Lake levels of three lakes in the vicinity of Lake Victoria–Lake Kyoga, Lake Albert, and Lake Edward – were not available from the USDA Reservoir Database. Altimetric lake heights for these lakes were instead provided by LEGOS/GOHS (Laboratoire d'Etudes en Geodesie et Oceanographie Spatiales, Equipe Geodesie, Oceanographie, et Hydrologie Spatiales), part of the French space agency CNES, from http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/. The LEGOS/GOHS time series are based on data from a combination of satellites: Topex/Poseidon, ERS-2, GFO, Jason-1, and ENVISAT.

ICESat

The LEGOS/GOHS time series of lake levels of Lake Kyoga ends in mid-2005. To extend this time series, data from NASA's Ice, Cloud, and land Elevation Satellite (ICESat) were used. ICESat, launched in January 2003, combines data from a downward-looking laser altimeter with GPS and satellite laser tracking data to determine geocentric elevations of the Earth's surface (Zwally et al., 2002). ICESat's primary objective is to measure elevation changes of the polar ice sheets, but high-quality elevation measurements can be obtained for other regions as well, including from surfaces of lakes. We have used results from ICESat to determine surface elevations of Lake Kyoga. Problems with the on-board lasers have lead to a reduced duty cycle, with sparser spatial and temporal sampling than was anticipated pre-launch. The availability of Lake Kyoga data is further reduced by the fact that this region of East Africa is frequently covered with dense clouds that cannot be penetrated by the laser altimeter. In fact, usable Lake Kyoga ICESat data are limited to just eight flyovers through March, 2008. We have edited those data to remove points with out-of-bounds saturation values, and we have applied the saturation correction and removed the EGM2008 geoid (http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/) from the remaining data.

Each flyover results in 20–100 points, where each point represents a return from a single along-track point. All data points for each flyover were averaged to obtain a single lake height. Some of the scatter in the points for a single flyover reflects random measurement errors, which largely cancel upon averaging, and some is a consequence of errors in the EGM2008 geoid that has been removed from the data. These latter errors are not random along a track, but appear as systematic along-track trends that tend to look the same for every flyover of the same track. With multiple repeat tracks, a geoid correction could be calculated and removed, but because there are so few usable flyovers of individual tracks, this is not practical in this case. We estimate that the geoid errors contribute 5–10 cm to the uncertainty in the ICESat lake height values. For times between data points, we estimate lake heights by linear interpolation.

Gravimetric terrestrial water storage

The Gravity Recovery and Climate Experiment (GRACE) satellite mission, sponsored by NASA and its German counterpart DLR, has been collecting data since mid-2002. The nominal data products are monthly Earth gravity fields (Tapley et al., 2004). These can be used to make global estimates of total vertically integrated water storage (TWS) with a spatial resolution of a few 100 km and greater, with higher accuracy at larger spatial scales (Wahr et al., 2004). We use Release-4 data produced by the Center for Space Research at the University of Texas. Each monthly GRACE gravity field consists of a set of spherical harmonic (Stokes) coefficients. After removal of the temporal mean, each monthly GRACE field is filtered using the method of Swenson and Wahr (2006), and converted to mass in units of equivalent water thickness. These fields are then spatially averaged to create a time series of total water storage anomalies. Swenson and Wahr (2007) compared water storage anomalies from GRACE to Jason-1 sea surface height variations averaged over the Caspian Sea, and found the two time series to be quite consistent at seasonal and inter-annual timescales, with an rms difference of about 5 cm.

Precipitation

Precipitation estimates beginning in 1998 are provided by the Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al., 1998), which is a joint mission of NASA and the National Space Development Agency (NASDA) of Japan. The primary instruments on the TRMM platform are the TRMM Microwave Imager (TMI), a nine-channel passive microwave radiometer, and the TRMM precipitation radar (PR), the first rain radar in space. Additional observations of cloud-top temperatures and structures is provided by the Visible and Infrared Radiometer System (VIRS). Here we use the TRMM 3B43 product, which is created by combining TRMM data with SSM/I, VIS/IR and rain gage data (Huffman et al., 2007). The resulting product is available with monthly temporal and 0.25 by 0.25 degree spatial resolution. Dinku et al. (2007) compared various satellite-based precipitation products to 120 rain gages distributed throughout the Ethiopian highlands to the northeast of the Lake Victoria region. They found typical errors in the TRMM 3B43 rain rates with rms values of 25% and biases of 10%. Using data from over 900 gages in West Africa, Nicholson et al. (2003) determined rms errors of about 1 $\frac{\text{mm}}{\text{day}}$ for monthly TRMM-merged rainfall estimates.

Evaporation bulk formulae datasets

Evaporation is perhaps the most difficult component of the lake's water budget to estimate. Direct estimates of evaporation, obtained by eddy covariance methods, cannot be made from satellite, so bulk formulae, which do not require the measurement of turbulent fluxes, are typically employed instead. The input to the bulk formulae are the surface and near-surface atmospheric state variables: wind, temperature, humidity, and pressure (Large and Yeager, 2004). Here we use satellite-derived wind speeds, sea surface temperatures, and near-surface atmospheric humidity and temperature; surface pressure is obtained from European Center for Medium-Range Weather Forecasting ECMWF operational analyses (ECMWF/WCRP, 1999).

The SeaWinds instrument on the QuikSCAT satellite is a microwave radar that measures near-surface wind speed and direction over the oceans and large inland water bodies (Callahan et al., 2006). Changes in wind velocity are related to changes in ocean surface roughness that modify the properties of the backscattered microwave pulses. Gridded data are available at 0.25-degree by 0.25-degree spatial and daily temporal resolution.

The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, on NASA's AQUA satellite, measures infrared radiation upwelling from the Earth's surface (Esaias et al., 1998). MODIS senses 36 spectral bands, with global coverage every 1–2 days. The IR radiances are used to estimate the skin (upper 1 mm or less) sea surface temperature (SST), which is then related to subsurface, or bulk, SST in the mixed layer. Here we use Level-3 data, binned to 8 day temporal and 9 km spatial resolution.

Near-surface temperature and humidity are estimated by combining data from multiple satellites. Jackson et al. (2006) merged microwave data from the Advanced Microwave Sounding Unit-A (AMSU-A) on the National Oceanic and Atmospheric Administration NOAA-15 satellite with Special Sensor Microwave Imager (SSM/I) and Special Sensor Microwave Temperature Sounder (SSM/T-2) data from five Defense Meteorological Satellite Program (DMSP) satellites. Using linear regression, Jackson et al. (2006) developed a relationship between atmospheric temperature and humidity measured by shipborne instruments and satellite brightness temperatures at multiple frequencies.

In situ lake outflow

Recently, tabulated measurements of the outflow from the Nalubaale and Kiira dams have become available in a report produced by Power Planning Associates (PPA, 2007). The report lists monthly observations of dam discharge for the period 1950–2005. The report generally confirms the conclusions of Kull (2006) and Sutcliffe and Petersen (2007), who found that on the order of half of the decrease in Lake Victoria water levels during 2003–2005 was due to dam releases; the remainder of the water loss was attributed to drought conditions. To make these data consistent with the other data used to describe the lake water balance, we convert these data from units of volume per time to units of average height per time by dividing by the area of the lake.

Methods

Lake water balance

The water balance of Lake Victoria can be expressed by the following:

$$\frac{dS}{dt} = P - E + Q_{in} - Q_{out}, \tag{1}$$

where $\frac{dS}{dt}$ is the change in lake height with respect to time, P is the precipitation rate, E is the evaporation rate, Q_{in} is inflow to the lake from the surrounding catchment, and Q_{out} is outflow from the lake. Q_{in} can be further decomposed as

$$Q_{in} = Q_{surface} + Q_{subsurface}, \tag{2}$$

where $Q_{surface}$ and $Q_{subsurface}$ represent overland flow and baseflow, respectively. Each term describes the spatial average taken over the area of the entire lake, and these quantities are expressed as an average layer thickness per time, e.g. mm per month. Of the five variables comprising Eq. (1), three are currently amenable to measurement from satellite: $\frac{dS}{dt}$, P, and E. Changes in lake level are routinely measured by altimetric methods, and evaporation can be estimated over water by combining satellite observations of temperature, wind, and humidity. Precipitation is measured regardless of whether the surface is land or water. Lake inflow and outflow are not measured remotely, and therefore must be measured *in situ* or parameterized in terms of some observed quantity if the water budget is to be closed.

Estimating lake evaporation

Due to the difficulty of making the measurements required by the eddy covariance method, evaporation is typically estimated using the bulk aerodynamic parameterization, which is suitable for both satellite and *in situ* surface observations (Bentamy et al., 2003). In this formulation, evaporation estimates are based on observations of surface temperature and pressure, and near-surface atmospheric temperature, humidity, and wind speed. The near-surface measurements are taken at a reference height, z_0, which is typically 10 m. The expression for evaporation is

$$E = \rho_{air} C_e (q_{air} - q_{sat}) |U_{air}|, \tag{3}$$

where E is the rate of evaporation, expressed in units of water thickness per time, ρ_{air} is the air density, C_e is the bulk transfer coefficient of water vapor, q_{air} is the 10 m air specific humidity and q_{sat} is the specific humidity of the air at the lake's surface, which is assumed to be saturated, and U_{air} is the 10 m wind speed (Large and Yeager, 2004). Air density depends on air pressure, density, and humidity

$$\rho_{air} = \frac{P}{R_{gas} T_{air} (1 + 0.608 q_{air})}, \tag{4}$$

where P is the surface air pressure, and $R_{gas} = 287.04$ J/kg/K is the gas constant for dry air. The bulk transfer coefficient of water vapor varies with wind speed as

$$C_e = 3.46 \times 10^{-4} \sqrt{\frac{27}{U_{air}} + 1.42 + \frac{U_{air}}{1.309}}. \tag{5}$$

Saturated specific humidity depends on air pressure, P, and the saturation vapor pressure e_{sat}

$$q_{sat} = \frac{0.622 e_{sat}}{P - e_{sat}}, \tag{6}$$

which in turn varies with temperature

$$e_{sat} = 0.611 e^{\frac{17.3 T_{sfc}}{T_{sfc} + 237.3}}, \tag{7}$$

where T_{sfc} is the temperature in degrees Celsius.

In the preceding formulae, q_{air} and T_{air} are derived from NOAA and DMSP satellites, U_{air} is derived from QuikScat, T_{sfc} is derived from the MODIS instrument aboard AQUA, and P is obtained from ECMWF operational analyses.

Results

GRACE estimates of trends in total water storage

By fitting a linear trend to GRACE estimates of total water storage, areas of sustained water accumulation or depletion can be observed. The largest amplitude features in maps of trends produced by GRACE for the period of approximately 2002–2007 are thought to be related to melting ice in regions of Greenland, Antarctica, and Alaska (Velicogna and Wahr, 2006; Luthcke et al., 2006; Tamisiea et al., 2005). Of the remaining features, one of the largest is a negative trend in TWS in central and eastern Africa. Fig. 2 shows a map of the trends in the region of Lake Victoria derived from GRACE. To compute these trends, we smoothed each monthly field using a 300 km Gaussian filter, mapped the data to a one degree by one degree grid, and fit the time series at each gridpoint using an annual sine and cosine, semi-annual sine and cosine, mean, and linear trend.

Fig. 2 shows that during this time period, much of Africa between 0 and −20 degrees latitude experienced large decreases in water storage. The area of negative trend encompasses much of the Rift Valley region, extending from Lake Victoria in the north to Lake Malawi in the south. The largest trends occur in central Africa as well as the region surrounding and centered on Lake Victoria, with values approaching $-60\ \frac{\text{mm}}{\text{year}}$. The magnitude of the positive trends shown in Fig. 2 are significantly smaller, with a maximum of less than $17\ \frac{\text{mm}}{\text{year}}$. Awange et al. (2007) described how extensive droughts are a regular feature of the regional climate. In their study, the temporal characteristics of drought in the Lake Victoria region were examined for the period 1961–1999. In addition to numerous seasonal droughts, they cataloged five multi-year droughts during that 40 year period, each lasting 2–3 years on average. This implies that the large negative trends in water storage observed by GRACE, while severe, are not uncommon.

Regional altimetric comparison

The trends in TWS derived from GRACE shown in Fig. 2 confirm that much of East Africa suffered from significant drought during the period 2002–2007. Time series of altimetric lake heights show that many lakes in this region experienced declining water levels due to the drought. In addition to Lake Victoria, two more of the world's largest lakes can be found in East Africa: Lake Tanganyika and Lake Malawi. The time series of average lake levels for these three lakes are compared in Fig. 3. Fig. 3 shows that, from 2002 through 2006, lake levels decreased in all three lakes. The best-fitting linear trend to each time series for that period are −311, −227, and $-219\ \frac{\text{mm}}{\text{year}}$ for Victoria, Tanganyika, and Malawi, respectively. It is notable that the trend of Lake Victoria, which is the only one of the three lakes with extensive hydropower development, is roughly 40% greater in magnitude than the others. The cause of the greater negative trend of Lake Victoria has been shown to result from human management of the lake outflow (Kull, 2006; Sutcliffe and Petersen, 2007) rather than greater atmospheric demand relative to the regions surrounding Lake Tanganyika and Lake Malawi. Here we seek to confirm these results by comparing the trends in water storage in each lake's catchment to the trends in water stored in the lake itself. To assess the influence of climatic conditions, we isolate TWS trends of each lake's drainage area. Catchment-average (including each lake) time series of TWS were computed from GRACE data, and the changes in mass of the lake

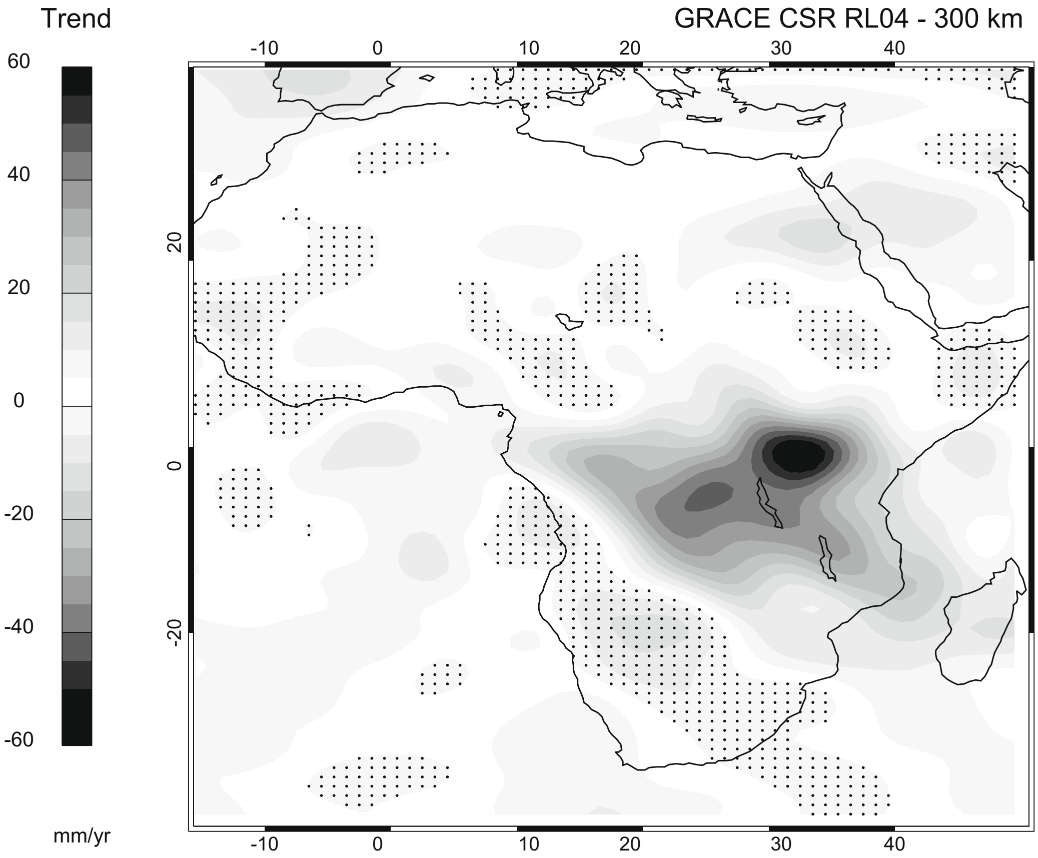

Fig. 2. Map of best-fitting linear trend in total water storage computed from monthly GRACE data for the period 2003–2007. Units are mm per year. Stippled regions indicate positive trends greater than $10\ \frac{\text{mm}}{\text{year}}$. Minimum/maximum trends are $-57\ \frac{\text{mm}}{\text{year}}$ and $17\ \frac{\text{mm}}{\text{year}}$, respectively.

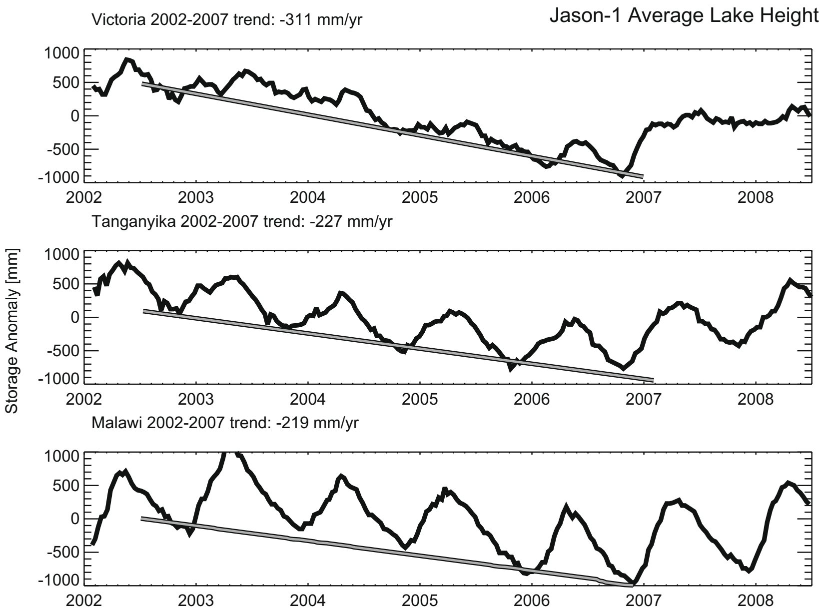

Fig. 3. Time series of altimetric lake levels for Lakes Victoria, Tanganyika, and Malawi. Gray lines represent best-fitting linear trends for the period 2003–2006. Units are mm.

were then removed using the altimetric data, resulting in time series of each lake's contributing watershed. Fig. 4 shows these time series. The best-fitting trends for each time series are −16, −27, and −18 $\frac{\text{mm}}{\text{year}}$ for Victoria, Tanganyika, and Malawi, respectively. Because GRACE measures total water storage, the TWS time series includes signals from the unsaturated zone (i.e. soil moisture) and the saturated zone (i.e. groundwater). The trends were calculated using the minimum storage values in each year in order to minimize the contribution from water in the unsaturated zone, and therefore primarily reflect changes in groundwater. The Lake Victoria watershed-only trend is actually smaller than the watershed-only trends of each of the other two lakes. This indicates that the Lake Victoria watershed experienced the same or less atmospheric demand than the watersheds of Lakes Tanganyika and Malawi.

At the catchment scale, changes in groundwater storage can be related to changes in groundwater levels by defining an effective drainable porosity (Brutsaert, 2008)

$$\frac{dS_{catchment}}{dt} = \eta \frac{dh_{groundwater}}{dt}, \tag{8}$$

where η is the effective drainable porosity. Lake levels are related to the water table because the boundary of the lake occurs where the water table intersects the land surface. The slope of the water table adjusts to changes in the lake boundary condition. Thus, a decrease in lake height results in a steeper water table slope, leading to enhanced lake inflow, which after some time acts to return the water table to its equilibrium profile. If one assumes that the water table changes via a series of such quasi-equilibrium states at annual and

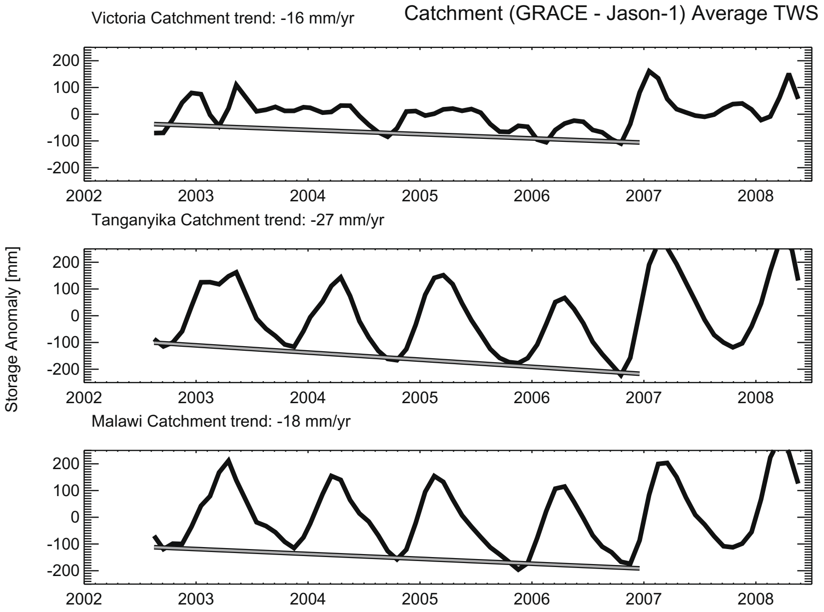

Fig. 4. Time series of total catchment water storage from GRACE minus altimetric lake levels for Lakes Victoria, Tanganyika, and Malawi. Gray lines represent best-fitting linear trends for the period 2003–2006. Units are mm.

longer periods, changes in average groundwater levels occur at approximately the same rate as changes in lake levels,

$$\frac{dS_{lake}}{dt} \simeq \frac{dh_{groundwater}}{dt}. \qquad (9)$$

Then η can be estimated by taking the ratio of the watershed- and lake-only trends, i.e.

$$\eta = \frac{dS_{catchment}}{dt} \Big/ \frac{dS_{lake}}{dt}. \qquad (10)$$

Using the trends for Lakes Tanganyika and Malawi, one obtains an average drainable porosity of about 0.1. The use of this value to estimate the natural lake-only trend from the watershed-only trend for Lake Victoria gives a trend of $-160 \frac{\mathrm{mm}}{\mathrm{year}}$, or about 51% of the observed lake-only trend for Lake Victoria, implying that roughly 49% of the decrease in lake level is due to enhanced lake outflow. From this result one can infer that the relative effects of the drought and human management are of similar size, a conclusion also reached by Kull (2006) and Sutcliffe and Petersen (2007).

Lake water budget components

Despite its great size, Lake Victoria has been significantly altered by human management in recent years. To inform and direct future management of the lake, it is necessary to understand the historical variability of the lake's level and the fluxes that control it. A climatological water balance based on the period 1956–1978 has been described by Piper et al. (1986) and Awange et al. (2007) calculated drought frequency statistics based on data from the period 1961–1999. More recent observations of the water balance are needed to extend these records, and to quantify the effects of human management and climate change.

Direct observations

Of the five terms of the water budget of Lake Victoria, three components (the change in total water storage, $\frac{dS}{dt}$, precipitation, P, and evaporation, E) can be estimated via satellite. Lake outflow, measured *in situ* by the operators of the Kiira and Nalubaale dams, has recently become publically available for the period 1950 through 2005 (PPA, 2007). Fig. 5 shows the observed components of the lake's water budget, smoothed with a moving 30-day boxcar filter. The top panel shows the time series of water storage anomalies, and the second panel shows the derivative of the water storage time series. The average annual change in water storage is $-373 \frac{\mathrm{mm}}{\mathrm{year}}$. Mean annual precipitation over the lake, shown in the third panel, is $1166 \frac{\mathrm{mm}}{\mathrm{year}}$, which during this period is about 70% of the annual evaporation of $1784 \frac{\mathrm{mm}}{\mathrm{year}}$, shown in the fourth panel. Lake outflow averages $558 \frac{\mathrm{mm}}{\mathrm{year}}$. The net contribution of these four components of the water balance is $803 \frac{\mathrm{mm}}{\mathrm{year}}$, which must be offset by surface and subsurface inflows to the lake.

Lake inflow

Observations of lake inflow, Q_{in}, and outflow, Q_{out}, are not currently available by remote sensing techniques. As shown in Eq. (2), Q_{in} may be separated into surface and subsurface flows. Surface flows are typically measured *in situ* at gaging stations, but a complete accounting of all the tributaries discharging into Lake Victoria is unavailable. However, because of the relatively small size of the lake's catchment, surface flow can be modeled as being proportional to precipitation. The justification is as follows: the effective radii of the catchment and the lake (computed as $\sqrt{\frac{area}{\pi}}$) are approximately 286 and 148 km, respectively. Thus, typical distances from the basin divides to the lake are of the order 140 km. Miller et al. (1994) estimated flow velocities for many rivers throughout the world and found average values in the range 30–100 cm/s. Based on this range of flow velocities, travel times for Lake Victoria tributary flows would be between 2 and 5 days, and therefore one would expect surface flows to be well correlated with precipitation at timescales of a month and longer.

Subsurface flows are not typically measured, but can be related to groundwater storage. Brutsaert (2008) showed that a linear relationship between groundwater storage and baseflow gave good agreement between well levels and annual low flows in Illinois. A subsequent study in Mongolia further supported this method (Brutsaert and Sugita, under review). Based on these results, we model variations in subsurface flow as being proportional to the watershed-only water storage time series described in "Regional altimetric comparison".

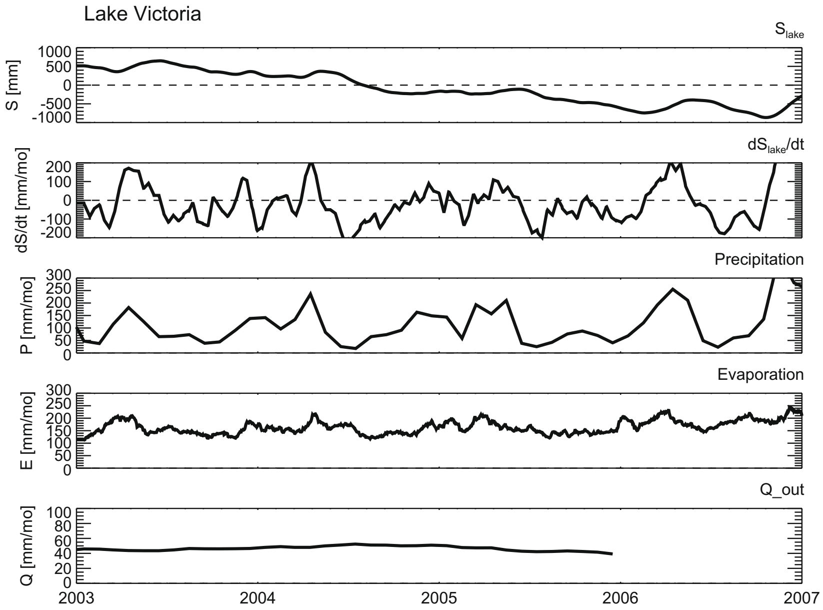

Fig. 5. Observed components of the Lake Victoria water balance for the period 2003–2006. From top to bottom, the time series are: total water storage anomaly, time derivative of TWS, precipitation, evaporation, and lake outflow. Note that lake outflow observations are only available for 2003–2005. All units are mm per month, except S, which has units of mm.

$$q = K_{subsurface} S_{catchment} + \overline{Q}_{subsurface}, \tag{11}$$

where q is baseflow, S is catchment water storage, and $K_{subsurface}$ is a proportionality constant. $\overline{Q}_{subsurface}$, which represents the mean value of subsurface flow, is necessary because the catchment TWS time series is derived in part from GRACE data, and therefore represents time variable rather than total values. This model of the Lake Victoria water balance has three unknown constants: the fraction of catchment precipitation that becomes surface runoff ($K_{surface}$), the proportionality constant between catchment TWS and subsurface flow ($K_{subsurface}$), and the mean value of subsurface flow ($\overline{Q}_{subsurface}$). The water balance of Lake Victoria then can be written as

$$\frac{dS_{lake}}{dt} = P - E + K_{surface} P + K_{subsurface} S_{catchment} + \overline{Q}_{subsurface} - Q_{out}. \tag{12}$$

Model inversion

The three constants are determined by a linear least squares inversion of the monthly averaged time series for the period of 2003–2005 where $\frac{dS_{lake}}{dt}, P, E, \frac{dS_{catchment}}{dt}$, and Q_{out} are concurrently measured. As a result of the least squares inversion, the three coefficients $K_{surface}, K_{subsurface}$, and $\overline{Q}_{subsurface}$ take values of 0.18, 0.38 $\frac{1}{\text{month}}$, and 35.34 $\frac{\text{mm}}{\text{month}}$, respectively. Fig. 6 shows the results of using these coefficients to compute the surface and subsurface components of Q_{in}. The top panel shows precipitation (gray line) and evaporation (black line) for reference. The second panel shows net precipitation, i.e. $P - E$, (black line) relative to $\frac{dS_{lake}}{dt}$ (gray line); the coefficient of correlation (R^2) between these time series is 0.84. The third panel shows $Q_{surface}$ (gray line) and $Q_{subsurface}$ (black line). The physical interpretation of the coefficients used to create these time series are as follows. $K_{surface}$ implies that approximately 18% of the watershed precipitation is converted to surface runoff that reaches Lake Victoria, with an annual average of 384 mm, the remainder being converted to evaporation, transpiration, or infiltration. $\frac{1}{K_{subsurface}}$, which represents the characteristic timescale of the catchment drainage process Brutsaert (2008), is about 2.7 months. This value is larger than the value obtained by Brutsaert (2008), and the discrepancy may be due to the effects of water storage other than groundwater in the catchment TWS time series. Swenson et al. (2006, 2008) examined water storage in Illinois and Oklahoma, USA, respectively, and found that the variability of water storage in the unsaturated and saturated zones was well correlated and of roughly equal magnitude. If similar conditions hold in the Lake Victoria catchment, one would expect a larger value of $K_{subsurface}$, and therefore a shorter drainage timescale, concordant with the value of 1.5 months obtained by Brutsaert (2008). Groundwater flow to the lake averages about 35 $\frac{\text{mm}}{\text{month}}$, or 420 $\frac{\text{mm}}{\text{year}}$, slightly larger than $K_{surface}$ during this period.

Comparison to previous studies

These values for the annual mean water balance components are generally consistent with other studies. Awange et al. (2007) noted that approximately 80% of the water input to the lake comes from direct rainfall while 20% derives from river discharge. If subsurface inflows are excluded, we obtain similar results; on average during 2003–2005 about 25% of the water input derives from surface inflows, and during the wettest year in this period (2006), the fraction is 21%. Yin and Nicholson (1998), investigating the period 1956–1978, calculated mean annual values of 1791 mm for precipitation, 1551 mm for evaporation, 343 mm for river inflow, and 524 for lake outflow. Their value of precipitation is within the range of values found here. The lowest mean annual precipitation in our study, 1046 mm, occured in 2003, and the highest, 1916 mm, occured in 2006. Our mean annual evaporation is over 200 mm higher than their preferred value of 1551 mm, which was based on an energy balance approach. However, Yin and Nicholson (1998) also estimated lake evaporation using the Penman method, which resulted in a value of 1743 $\frac{\text{mm}}{\text{year}}$; this value compares more favorably to our value of 1784 mm. They chose the lower value because it provided better closure to their water balance, but the lake inflow component of their water balance model neglected baseflow. Our analysis indicates baseflow may contribute as much as a few hundred mm of water to the lake each year, and thus the higher evaporation estimate of Yin and Nicholson (1998) may be more appropriate. Our surface inflow value is similar (about 11% higher) to that of Yin and Nicholson (1998).

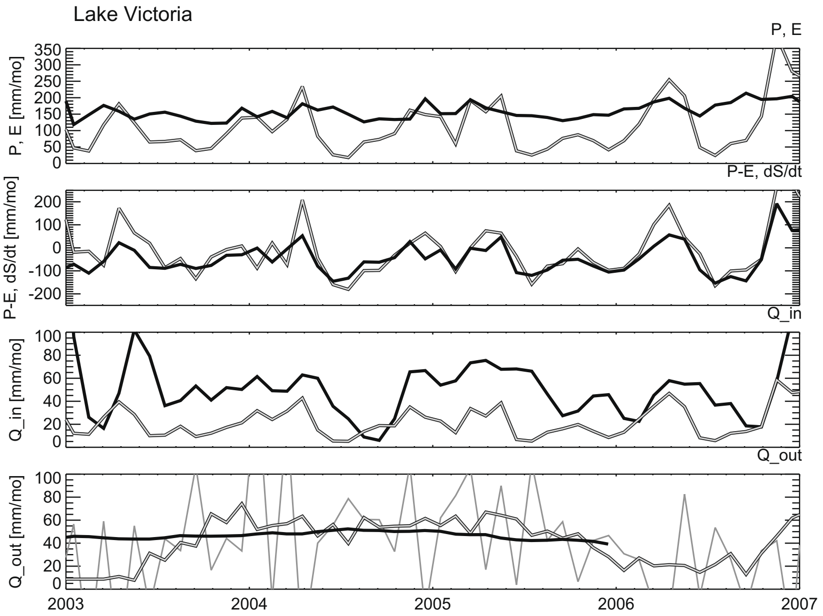

Fig. 6. Top panel: comparison of P (gray line) and E (black line); second panel: net precipitation ($P - E$, black line) and $\frac{dS}{dt}$ (gray line); third panel: $Q_{surface}$ (gray line) and $Q_{subsurface}$ (black line); fourth panel: estimated monthly lake outflow (thin gray line), observed lake outflow (black line), estimated lake outflow, smoothed with 6-month running boxcar average (light gray line). All units are mm per month.

Lake outflow

Having determined the lake inflow coefficients using the observed lake outflow for 2003–2005, it is now possible to use those coefficients to estimate lake outflow for times when observations are unavailable, i.e after the end of 2005, by computing outflow as a residual term in the water balance. The fourth panel of Fig. 6 shows the observed lake outflow (black line) and the estimated outflow (light gray line). The estimated outflow exhibits unrealistic monthly variability $\left(\text{rmse} = 51\ \frac{\text{mm}}{\text{month}}\left(1355\ \frac{\text{m}^3}{\text{s}}\right)\right)$, due to noise in the $P - E$ and $\frac{dS_{lake}}{dt}$ time series shown in the second panel from the top. By filtering out the short period variability, however, a reasonable estimate of outflow is obtained. After smoothing with a moving 6-month boxcar filter (dark gray line), the standard deviation of the difference between the estimated and observed outflow is 17 $\frac{\text{mm}}{\text{month}}\left(452\ \frac{\text{m}^3}{\text{s}}\right)$. Much of the difference occurs in the first half of 2003. An examination of the monthly precipitation time series shows that peak values in 2003 are the lowest of any year, while the changes in lake height are comparable to other years. The introduction in 2000–2002 of data from the AMSU-B instrument into the TRMM 3B43 precipitation estimates led to a low bias, which was addressed by a revised algorithm applied in July of 2003 (Huffman et al., 2007). The low precipitation values in 2003 may be the result of this bias. The rms difference between the smoothed and observed outflow drops to 11 $\frac{\text{mm}}{\text{month}}\left(292\ \frac{\text{m}^3}{\text{s}}\right)$ if the first 6 months of the time series are excluded.

Typical changes in discharge for the period 2003–2006 are on the order of 5 $\frac{\text{mm}}{\text{month}}$, so even after smoothing, the estimated discharge is too noisy to reliably estimate typical monthly lake outflows. In 2006, the estimated outflow indicates that discharge from the lake was possibly reduced, prior to increasing toward the levels of the previous 3 years. The reduction of about 20 $\frac{\text{mm}}{\text{month}}$ after the beginning of 2006 is greater than the 11 $\frac{\text{mm}}{\text{month}}$ rms difference, but not enough to give great confidence in the estimate.

Estimating Lake Victoria outflow from downstream lake levels

The results of "Lake water budget components" indicate that the currently available set of remotely sensed observations of Lake Victoria are not sufficiently accurate to estimate the outflow as a residual. It may be possible, however, to estimate Lake Victoria's outflow from satellite by focusing on regions that are downstream of the lake. From Lake Victoria, water travels north where it enters Lake Kyoga, then flows west to Lake Albert. The open water area of Lake Kyoga is approximately 3740 km^2, or 20 times smaller than the area of Lake Victoria. Because of its smaller size, the water balance of Lake Kyoga is primarily controlled by the input of water from Lake Victoria rather than net precipitation and catchment inflow. For example, an outflow of 1000 $\frac{\text{m}^3}{\text{s}}$ would lower the level of Lake Victoria by 37 mm after one month, but the same inflow would raise Lake Kyoga by nearly 700 mm because of its smaller surface area.

The effects of variations in Lake Victoria discharge on downstream water bodies can be seen by comparing lake levels of Lake Kyoga to those of Lake Albert, which is downstream of Lake Kyoga, and Lake Edward, which is upstream of Lake Albert, but unconnected to Lake Victoria (Fig. 1). Lake levels of Lake Kyoga (top panel), Lake Albert (middle panel), and Lake Edward (bottom panel) are shown in Fig. 7 for the time period where altimetric lake heights are available for all three lakes. The Lake Kyoga time series produced by LEGOS/GOHS ends in mid-2005, so ICESat data was used to extend it through 2008. The time series of Lake Kyoga and Lake Albert, which both are downstream from Lake Victoria, show similar behavior; surface heights are relatively stable until mid-2005, when a large drop occurs. By mid-2006, Lake Kyoga lost about 1.5 m of water, and Lake Albert lost about 1 m of water. During that time period, Lake Victoria discharge was reduced from a high at the end of 2004 of over 1300 $\frac{\text{m}^3}{\text{s}}$ to a little more than 1000 $\frac{\text{m}^3}{\text{s}}$ at the end of 2005 (in this section we use units of $\frac{\text{m}^3}{\text{s}}$, in which discharge measurements are typically given; $1\ \frac{\text{m}^3}{\text{s}} = 0.7\ \frac{\text{mm}}{\text{month}}$ for Lake Kyoga). In contrast, Lake Edward, which is not fed by Lake Victoria, shows no drop. Instead, its time series generally trends downward until mid-2006, when it shows a slight increase. This behavior is consistent with other lakes in East Africa whose outflows are unmanaged, for example Lakes Tanganyika and Malawi (shown in Fig. 3).

Fig. 8 compares lake levels of Lake Victoria and Lake Kyoga (top and bottom panels, respectively) and observed discharge from Lake Victoria (middle panel). Because of Lake Kyoga's small size, its altimetric record is relatively noisier than that of Lake Victoria. Prior to 1998, all three time series are relatively stable, followed by rapid

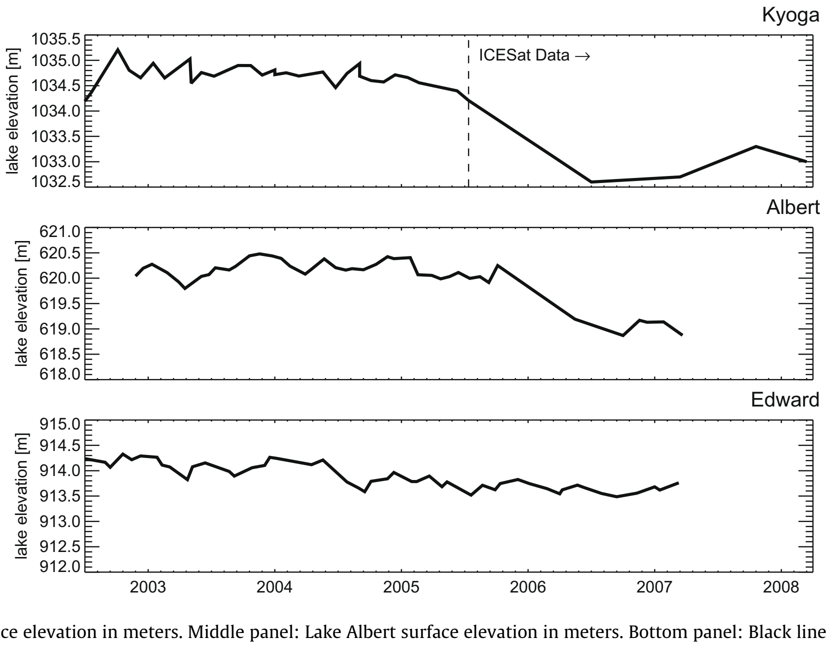

Fig. 7. Top panel: Lake Kyoga surface elevation in meters. Middle panel: Lake Albert surface elevation in meters. Bottom panel: Black line: Lake Edward surface elevation in meters.

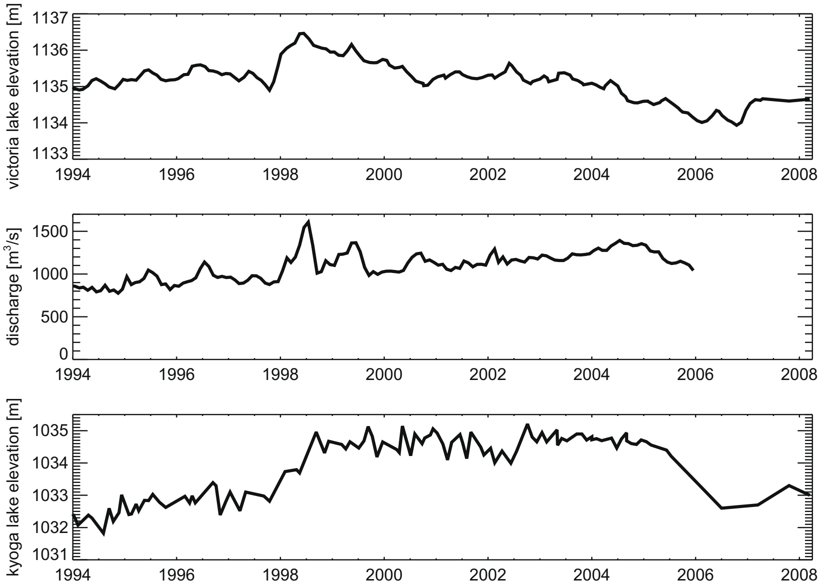

Fig. 8. Top panel: Lake Victoria surface elevation in meters. Middle panel: Lake Victoria discharge in $\frac{m^3}{s}$. Bottom panel: Black line: Lake Kyoga surface elevation in meters; light gray line: same, except smoothed with 6-month running boxcar average.

increases due to heavy precipitation during 1998. At that time, Lake Victoria rose by over a meter, while Lake Kyoga rose about 2 m. After 1999, the behavior of the three time series appear to diverge. While Lake Victoria Lake heights generally declined during 1999–2006, discharge increased for much of the time period, and lake levels in Lake Kyoga remained relatively stable. Thus, the increased discharge relative to the natural outflow specified by the "Agreed Curve" accelerated Lake Victoria's decline, while maintaining the levels in Lake Kyoga despite the regional drought.

The outflow from Lake Kyoga is not directly controlled by human management via dams, instead it is determined by variations in the level of the lake; in the case of Lake Victoria the converse is true, and dam operations control the lake level. Undisturbed lakes often can be well modeled as linear reservoirs, where outflow is proportional to water level (Dingman, 1994). For example, the "Agreed Curve" of Lake Victoria, which was designed to mimic natural flows prior to the construction of the Nalubaale Dam, specifies discharge as a nearly linear function of lake level (PPA, 2007). In a study produced by the Environmental Impact Assessment Centre of Finland (ILM, 2004), Lake Kyoga outflow during the period 1962–1997 was shown to obey a linear relationship with water levels, with a slope of approximately 460 $\frac{m^3}{s}$ per m. Using a linear relationship between outflow and lake level, e.g. $Q_{out} = kS + d$, Lake Kyoga's water balance may be expressed as

$$Q_{\text{Victoria}} = \frac{dS_{\text{Kyoga}}}{dt} + (kS_{\text{Kyoga}} + d) - (P - E + Q_{catchment}), \qquad (13)$$

where Q_{Victoria} is the input received from Lake Victoria, and $Q_{catchment}$ is the total surface and subsurface inflow from Lake Kyoga's catchment. Given observations of Q_{Victoria}, S, and $(P - E + Q_{catchment})$, Eq. (13) can be used to determine the coefficients k and d of the linear transfer function. Satellite estimates of precipitation over Lake Kyoga are available, but direct estimates of E and $Q_{catchment}$ are not due to the smaller spatial scale. However, assuming that the inputs of E, and $Q_{catchment}$ are of similar magnitude to those of Lake Victoria we find that their net contribution to the mean Lake Kyoga water budget is approximately an order of magnitude smaller than that of Q_{Victoria}. We therefore approximate E and $Q_{catchment}$ for Lake Kyoga with the time mean values calculated for Lake Victoria in "Lake water budget components".

Using a linear least squares inversion routine, the best-fitting values of the parameters k and d are $2.8 \times 10^{-3}\ \frac{m^2}{s}$ and $-2.89\ \frac{m^3}{s}$, respectively. The value of k is of the same order as the slope of the outflow-water level curve from the ILM (2004) report $\left(\frac{1}{460} = 2.2 \times 10^{-3}\ \frac{m^2}{s}\right)$. The d coefficient is related to the datum used to convert lake surface elevations to lake stage height, which can be seen by defining $d' = -d/k$. Then $kS + d = k(S - d')$, where the datum, $d' = 1025.1$ m, represents the lake elevation of zero outflow. Data only from the period 1993–1997 were used in the inversion to avoid possible non-linear effects related to the high precipitation in 1998. Fig. 9 shows the results of using the best-fitting values of k and d to solve for Q_{Victoria} in Eq. (13). The black line shows the observed values of Lake Victoria discharge, which are available until 2006. The light gray line shows the estimated Q_{Victoria} time series, based on the linear reservoir model. Near the bottom of the plot, in dark gray, the time series of $P - E + Q_{catchment}$ is shown, demonstrating that it contributes mainly to the high frequency variability of Q_{Victoria}, while S and its derivative determine the long period behavior.

For much of the time period shown, the estimated outflow from Lake Victoria agrees well with the observations (rmse= 134 $\frac{m^3}{s}$). This value is about an order of magnitude smaller than the rmse obtained by estimating Q_{Victoria} as a residual from the monthly water balance in "Lake water budget components". The estimated outflow exhibits the main features of the observed outflow, such as the lower magnitude pre-1998 flows, the rapid rise in 1998, the gradual decrease from 1999 to about 2002, and the large decrease in 2005. From about 2002–2005, the discharge from Lake Victoria increases, while the altimetric Lake Kyoga levels remain relatively constant. This disagreement is likely due to a change in the outflow-water level relationship caused by a blockage near the exit of Lake Kyoga after the intense rains of 1998. Many of the water bodies in this region, including Lake Kyoga, contain large floating mats of papyrus, called sudds. During periods of intense rain, these sudds can become dislodged and transported by currents. After the 1998 rains, sudds in Lake Kyoga became dislodged, and accumulated near the outlet of the lake (ILM, 2004). The sudd blockage caused a shift in the outflow-water level relationship that diminished in time as channels through the blockage developed.

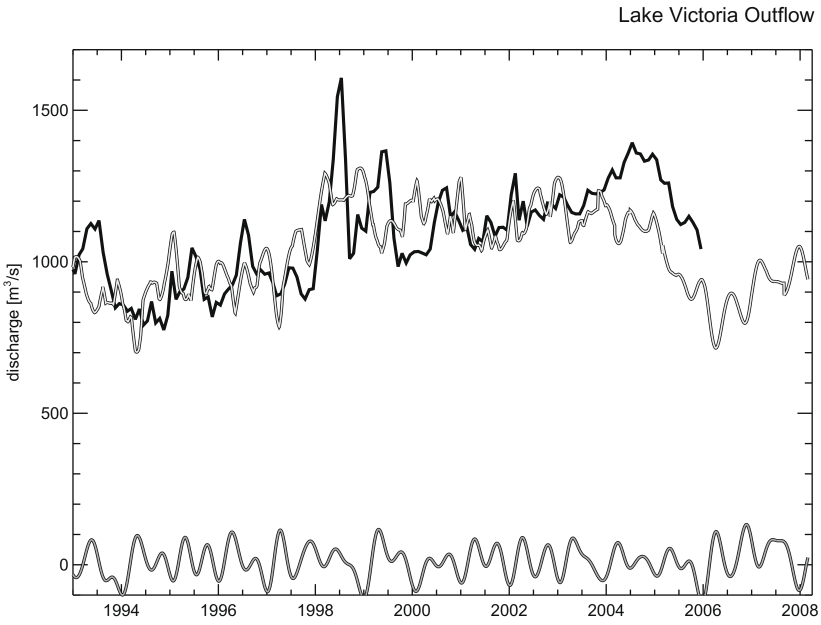

Fig. 9. Lake Victoria discharge in $\frac{m^3}{s}$. Black line: observed discharge; light gray line: estimated discharge, using the method based on Lake Kyoga lake levels; dark gray line: $P - E + Q_{catchment}$.

A comparison of outflow to water levels at a location downstream of the sudd blockage indicates that the outflow-water level relationship is only slightly changed (ILM, 2004), but the lake levels behind the blockage are somewhat higher. Because the altimetric lake heights sample the main body of the lake, they are therefore biased relative to the lake levels downstream of the blockage. This bias diminished with time; extrapolating the 1999–2003 data in the ILM (2004) report, one can infer a return to pre-1998 conditions around the end of 2005. Fig. 10 shows the original altimetric lake height (black line) and the corrected lake height (gray line). Repeating the calculation of k and d' using the bias-corrected lake level time series based on the ILM (2004) report, we obtain values of 2.3×10^{-3} $\frac{m^2}{s}$ and 1022.1 m, respectively. Fig. 11 shows the results of using the corrected lake levels to construct a time series of discharge from Lake Victoria. The black line shows the observed values of Lake Victoria discharge, and the light gray line shows the estimated Q_{Victoria} time series. The relatively large differences during the period 2003–2006 (shown in Fig. 9) are reduced, which is reflected in the rmse of 115 $\frac{m^3}{s}$, a reduction of about 15%. In this case, the bias correction was based on *in situ* data provided by the ILM (2004) report, but future laser altimeter missions may provide the necessary spatial resolution to determine the slope of the lake in addition to the mean lake height.

Discussion

Satellite observations, which are publically available and of high quality, are a powerful tool for monitoring the state of Lake Victo-

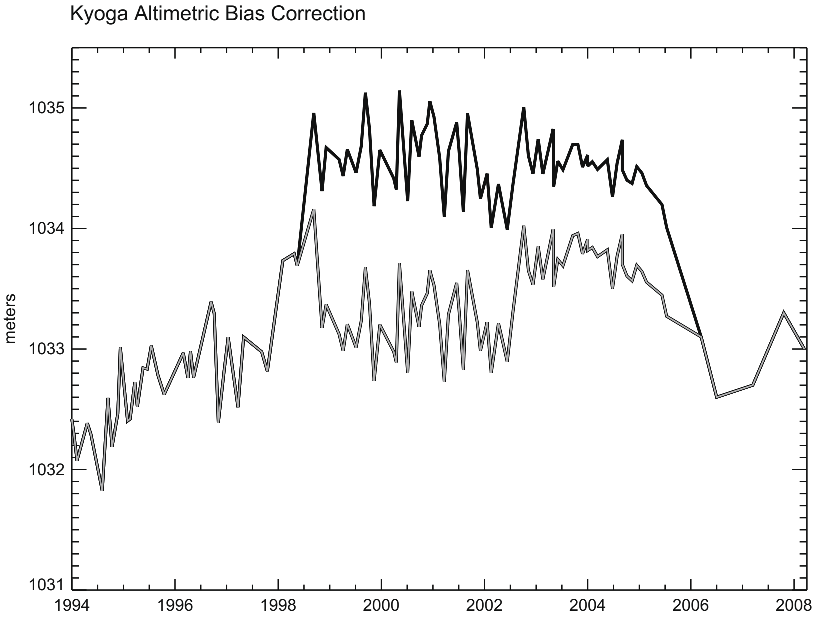

Fig. 10. Bias between lake heights measured mid-lake and at lake outlet, based on ILM (2004) report.

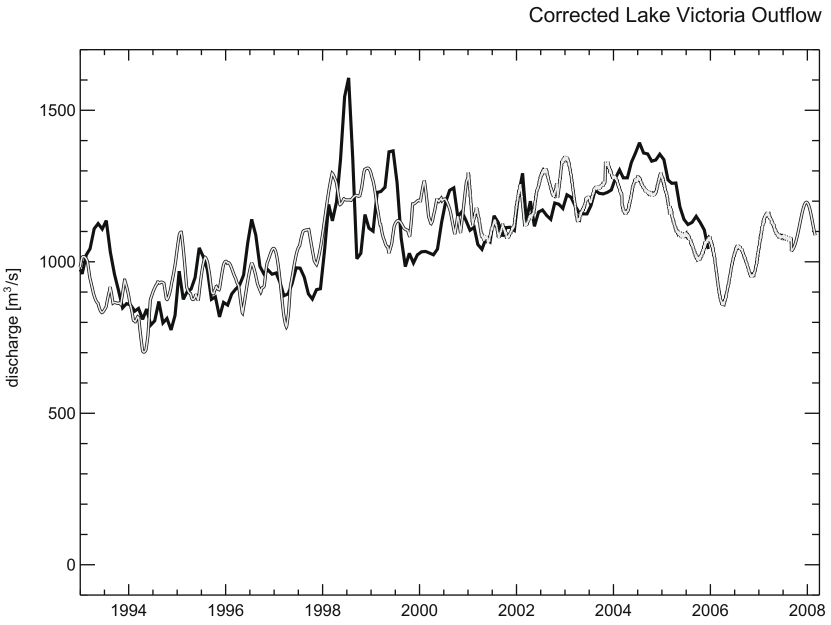

Fig. 11. Lake Victoria discharge in $\frac{m^3}{s}$. Black line: observed discharge, light gray line: estimated discharge after lake-level bias correction based on ILM (2004) report.

ria, as well as other ecologically sensitive regions of the world. In this study, we have estimated monthly components of the water balance of Lake Victoria and its surroundings using primarily satellite data, with *in situ* data needed only to calibrate a few parameters. Prior to the publication of the Power Planning Associates report (PPA, 2007), the relative impacts of climatic forcing and human management of Lake Victoria outflow on lake levels were unknown. The thorough analysis of Kull (2006) indicated that excessive (relative to the "Agreed Curve") dam discharge and drought played nearly equal roles in the lake's decline. However, because contemporaneous data were not readily available, the result was based on climatological data, and required ad hoc adjustments of those data to produce simulations of the lake's water balance. The release of the PPA report enabled Sutcliffe and Petersen (2007) to construct a naturalized lake level time series, i.e. the lake levels that would have occured if the "Agreed Curve" had been used to determine dam discharge. A comparison of their naturalized lake level time series to the actual lake levels measured by altimeter allowed them to partition the total lake level drop between natural climatic effects and over-abstraction. Sutcliffe and Petersen (2007) concluded that each effect contributed about half of the total drop in lake level, a result very similar to that of Kull (2006). We have further confirmed this conclusion through a comparative analysis of Lakes Victoria, Tanganyika, and Malawi. Lakes Tanganyika and Malawi provide a useful counterpoint because they have not been dammed for hydropower, and therefore their lake levels evolve mainly in response to regional climate variability.

An indication that Lake Victoria experienced extraction above natural rates can be seen by comparing the trends in lake levels of the three lakes; Lake Victoria levels fell about 40% faster than those of Lake Tanganyika and Lake Malawi. This fact by itself does not prove that the difference in the rates of lake decline is due to human management, because the possibility that Lake Victoria experienced a relatively greater decrease in net precipitation is not addressed. We examined the effects of regional differences in climatic forcing by also comparing trends in the time series of catchment water storage. The trend in dry season TWS for Lake Victoria's catchment actually declined less rapidly than the trends of the other lakes' catchments, indicating that the region around Lake Victoria did not experience enhanced drought conditions relative to Lakes Tanganyika and Malawi. Using a relationship between the trend in catchment water storage and the trend in lake level based on Lakes Tanganyika and Malawi, we then inferred that climate forcing explained about half of the trend of Lake Victoria lake levels, implying that excessive discharge contributed about an equal amount to the lake's decline. Next, we focused on the water balance of Lake Victoria. In addition to using operationally available lake height and precipitation data, time series of evaporation and lake inflow were constructed from other satellite-derived datasets. Previous studies utilized climatological estimates of evaporation subject to considerable uncertainty, while subsurface inflow was not included in the water balance due to a lack of observations. Our analysis indicates that baseflow may be a significant component of the water budget, and evaporation estimates of earlier studies may be biased low to compensate for its absence. At the monthly timescale, the water balance can be closed to within 51 $\frac{mm}{month}\left(1415\ \frac{m^3}{s}\right)$, and at seasonal timescales to within 17 $\frac{mm}{month}\left(445\ \frac{m^3}{s}\right)$. While this result is encouraging, it is not yet accurate enough to resolve typical month to month changes in lake outflow as a residual. Instead, these data will be valuable for assessing and improving the predictive capability of regional climate models (e.g. Anyah and Semazzi, 2007; Song et al., 2004) in order to better forecast periods of droughts and flooding in East Africa.

Obviously, the best estimates of lake outflow are measurements of discharge made at the Nalubaale and Kiira dams, but in the future, measurements of dam discharge such as those described in PPA (2007) may not be publically available. We have also described an alternative to measuring dam discharge directly by examining the water balance of lakes that are downstream of Lake Victoria. Past measurements of lake height and outflow show that Lake Kyoga acts as a linear reservoir (ILM, 2004). With this model, discharge from Lake Victoria can be estimated fairly accurately (rmse = 134 $\frac{m^3}{s}$) from remotely sensed lake heights of Lake Kyoga. Difficulties can arise due to departures from the linear model. In this case, restrictions at the lake outlet from floating mats of vegetation (sudd) introduced a bias between the average lake height, which is measured by an altimeter, and the outlet lake height, for which the linear relationship was valid. Fortunately, this bias was temporary, and average lake height and outlet lake height eventually converged, such that this method is apt to be useful in the future.

Following 2006, increased precipitation significantly reduced the water storage deficit accumulated during the previous few years. Lake levels in Lakes Tanganyika and Malawi, for example, have returned to or surpassed their 2003 values. Lake Victoria has also rebounded, but is still at its lowest levels since before 1960. Altimetric time series show that the level of the lake has been held relatively constant since mid-2007, implying that excess lake input has been used to produce hydroelectric power. While this may fulfill present day power needs, it fails to provide adequate water storage to withstand future drought. Examination of the historical records of lake height [http://www.fas.usda.gov/pecad/highlights/2005/09/uganda_26sep2005/images/2000_2005.htm] and precipitation (Awange et al., 2007) reveals a roughly decadal cycle of variability. If a drought begins while Lake Victoria's levels are at its current level, there will be very little storage to draw upon without greatly affecting the health of the lake.

The data provided in the PPA (2007) report answered many questions about the operation of Lake Victoria's dams, but such data may not be available in the future. Furthermore, construction of the new Bujagali dam, downstream of the Kiira and Nalubaale dams, is currently underway, and its effect on lake levels will be a source of concern for many of the lake's stakeholders. The ability of Lake Victoria's stakeholders to independently assess the lake's water balance, and especially the role of human management in controlling the water balance, will only become more important in the face of higher population and global climate change. The hydroclimatic state of the region around Lake Victoria appears to have shifted from prolonged drought to normal precipitation conditions in 2006, but unfortunately the historical record indicates that drought will likely return within the decade.

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Time series of altimetric lake level variations from the NASA/CNES Topex/Poseidon and Jason-1 satellite missions were obtained from the USDA Reservoir Database at http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir. Additional altimetric lake level variations from LEGOS/GOHS were obtained at http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/. The QuikScat wind speed data and MODIS sea surface temperature data were obtained through the online PO.DAAC Ocean ESIP Tool (POET) at the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at the NASA Jet Propulsion Laboratory, Pasadena, CA. http://podaac.jpl.nasa.gov.

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