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Recent changes in terrestrial water storage in the Upper Nile Basin: an evaluation of commonly used gridded GRACE products

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Abstract. GRACE (Gravity Recovery and Climate Experiment) satellite data monitor large-scale changes in total terrestrial water storage (ΔTWS), providing an invaluable tool where in situ observations are limited. Substantial uncertainty remains, however, in the amplitude of GRACE gravity signals and the disaggregation of TWS into individual terrestrial water stores (e.g. groundwater storage). Here, we test the phase and amplitude of three GRACE ΔTWS signals from five commonly used gridded products (i.e. NASA's *GRCTellus*: CSR, JPL, GFZ; JPL-Mascons; GRGS GRACE) using in situ data and modelled soil moisture from the Global Land Data Assimilation System (GLDAS) in two sub-basins (LVB: Lake Victoria Basin; LKB: Lake Kyoga Basin) of the Upper Nile Basin. The analysis extends from January 2003 to December 2012, but focuses on a large and accurately observed reduction in ΔTWS of 83 km^3 from 2003 to 2006 in the Lake Victoria Basin. We reveal substantial variability in current GRACE products to quantify the reduction of ΔTWS in Lake Victoria that ranges from 80 km^3 (JPL-Mascons) to 69 and 31 km^3 for GRGS and *GRCTellus* respectively. Representation of the phase in TWS in the Upper Nile Basin by GRACE products varies but is generally robust with GRGS, JPL-Mascons, and *GRCTellus* (ensemble mean of CSR, JPL, and GFZ time-series data), explaining 90, 84, and 75 % of the variance respectively in "in situ" or "bottom-up" ΔTWS in the LVB. Resolution of changes in groundwater storage (ΔGWS) from GRACE ΔTWS is greatly constrained by both uncertainty in changes in soil-moisture storage (ΔSMS) modelled by GLDAS LSMs (CLM, NOAH, VIC) and the low annual amplitudes in ΔGWS (e.g. 1.8–4.9 cm) observed in deeply weathered crystalline rocks underlying the Upper Nile Basin. Our study highlights the substantial uncertainty in the amplitude of ΔTWS that can result from different data-processing strategies in commonly used, gridded GRACE products; this uncertainty is disregarded in analyses of ΔTWS and individual stores applying a single GRACE product.

1 Introduction

Satellite measurements under the Gravity Recovery and Climate Experiment (GRACE) mission have, since March 2002 (Tapley et al., 2004), enabled remote monitoring of large-scale (i.e. GRACE footprint: ~ 200 000 km^2), spatio-temporal changes in total terrestrial water storage (ΔTWS) at 10-day to monthly timescales (Longuevergne et al., 2013; Humphrey et al., 2016). Over the last 15 years, studies in basins around the world (Rodell and Famiglietti, 2001; Strassberg et al., 2007; Leblanc et al., 2009; Chen et al., 2010; Longuevergne et al., 2010; Frappart et al., 2011; Jacob et al., 2012; Shamsudduha et al., 2012; Arendt et al., 2013; Kusche et al., 2016) have demonstrated that GRACE satellites trace natural (e.g. drought, floods, glacier and ice melting, sea-level rise) and anthropogenic (e.g. abstraction-driven groundwater depletion) influences on ΔTWS. GRACE-derived TWS provides vertically integrated water storage changes in all water-bearing layers (Wahr et al., 2004; Strassberg et al., 2007; Ramillien et al., 2008) that include (Eq. 1) surface water storage in rivers, lakes, and wetlands (ΔSWS), soil moisture storage (ΔSMS), ice and snow water storage (ΔISS), and groundwater storage (ΔGWS). Over the last decade, GRACE measurements have become an important hydrological tool for quantifying basin-scale ΔTWS (Güntner, 2008; Xie et al., 2012; Hu and Jiao, 2015) and are increasingly being used to assess spatio-temporal changes in specific water stores (Famiglietti et al., 2011; Shamsudduha et al., 2012; Jiang et al., 2014; Castellazzi et al., 2016; Long et al., 2016; Nanteza et al., 2016) where time-series records of other individual freshwater stores are available (Eq. 1).

$$\Delta \mathrm{TWS}_t = \Delta \mathrm{GWS}_t + \Delta \mathrm{ISS}_t + \Delta \mathrm{SWS}_t + \Delta \mathrm{SMS}_t \quad (1)$$

GRACE-derived ΔTWS derive from monthly gravitational fields which can be represented as spherical harmonic coefficients that are noisy as depicted in north–south elongated linear features or "stripes" on monthly global gravity maps (Swenson and Wahr, 2006; Wang et al., 2016). Post-processing of GRACE SH data is therefore required. The most popular GRACE products are NASA's *GRCTellus* land gravity solutions (i.e. spherical harmonics based CSR, JPL, and GFZ), which require scaling factors to recover spatially smoothed TWS signals (Swenson and Wahr, 2006; Landerer and Swenson, 2012). Additionally, NASA's new monthly gridded GRACE product, Mass Concentration blocks (i.e. Mascons), estimates terrestrial mass changes directly from inter-satellite acceleration measurements and can be used without further post-processing (Rowlands et al., 2010; Watkins et al., 2015). GRGS GRACE products are also spherical harmonic-based, available at a 10-day time step, and can also be used directly since gravity fields are stabilized during the processing of GRACE satellite data (Lemoine et al., 2007; Bruinsma et al., 2010).

Restoration of the amplitude of *GRCTellus* TWS data, dampened by spatial Gaussian filtering with a large smoothing radius (e.g. 300–500 km), is commonly achieved using scaling factors that derive from a priori models of freshwater stores, usually a global-scale land-surface model or LSM (Long et al., 2015). However, signal-restoration methods are emerging that do not require hydrological models or LSMs (Vishwakarma et al., 2016). Substantial uncertainty nevertheless persists in the magnitude of applied scaling factors (e.g. *GRCTellus*) and corrections (Long et al., 2015). Recent global-scale analyses have evaluated variability in the amplitude of ΔTWS in various GRACE products (Scanlon et al., 2016) and compared these with evidence from global hydrological and land-surface models (Long et al., 2017); these studies highlight well uncertainties in the amplitude of ΔTWS, but are not reconciled to observations. In situ observations provide a valuable and necessary constraint to the scaling of TWS signals over a particular study area, as no consistent basis for ground-truthing these factors exists.

The disaggregation of GRACE-derived ΔTWS anomalies into individual water stores (Eq. 1) is commonly constrained by the limited availability of observations of terrestrial freshwater stores (i.e. ΔSWS, ΔSMS, ΔGWS, and ΔISS). Indeed, a major source of uncertainty in the attribution of GRACE ΔTWS derives from the continued reliance on modelled ΔSMS derived from LSMs (i.e. CLM, NOAH, VIC, and MOSAIC) under the Global Land Data Assimilation System or GLDAS (Rodell et al., 2004) and remote-sensing products (Shamsudduha et al., 2012; Khandu et al., 2016). Further, analyses of GRACE-derived ΔGWS often assume ΔSWS is limited (Kim et al., 2009), yet studies in the humid tropics and engineered systems challenge this assumption, showing that it can overestimate ΔGWS (Shamsudduha et al., 2012; Longuevergne et al., 2013). Robust estimates of ΔGWS from GRACE gravity signals have, to date, been developed in locations where ΔSWS is well constrained by in situ observations and groundwater is used intensively for irrigation so that ΔGWS comprises a significant ($> 10\,\%$) proportion of ΔTWS (Leblanc et al., 2009; Famiglietti et al., 2011; Shamsudduha et al., 2012; Scanlon et al., 2015). In sub-Saharan Africa, intensive groundwater withdrawals are restricted to a limited number of locations (e.g. irrigation schemes, cities) and constrained by low-storage, low-transmissivity aquifers in the deeply weathered crystalline rocks that underlie $\sim 40\,\%$ of this region (MacDonald et al., 2012), including the Upper Nile Basin (Fig. 1). Consequently, the ability of low-resolution GRACE gravity signals to trace ΔGWS in these hard-rock environments is unclear. A recent study (Nanteza et al., 2016) applies NASA's *GRCTellus* (CSR GRACE) data over large basin areas ($> 300\,000\,\mathrm{km}^2$) of eastern Africa and argues that ΔGWS can be estimated with sufficient reliability to characterize regional groundwater systems after accounting for ΔSWS by satellite altimetry and ΔSMS data from the GLDAS LSM ensemble (Rodell et al., 2004).

Here, we exploit a large-scale reduction and recovery in surface water storage that was recorded within Lake Victoria (Fig. 1), the world's second largest lake by surface area ($67\,220\,\mathrm{km}^2$) (UNEP, 2013) and eighth largest by volume ($2760\,\mathrm{km}^3$) (Awange et al., 2008). This well-constrained reduction in ΔSWS comprises a decline in lake level of 1.2 m between May 2004 and February 2006, equivalent to a lake-water volume (ΔSWS) loss of $81\,\mathrm{km}^3$ that resulted, in part, from excessive dam releases (Fig. 2). We test the ability of current GRACE products to represent the amplitude and phase of this voluminous and well-constrained change in freshwater storage. Our analysis focuses on both the Lake Victoria Basin (hereafter LVB) ($256\,100\,\mathrm{km}^2$) and Lake Kyoga Basin (hereafter LKB) ($79\,270\,\mathrm{km}^2$) (Fig. 1). Applying in situ observations of ΔSWS and ΔGWS com-

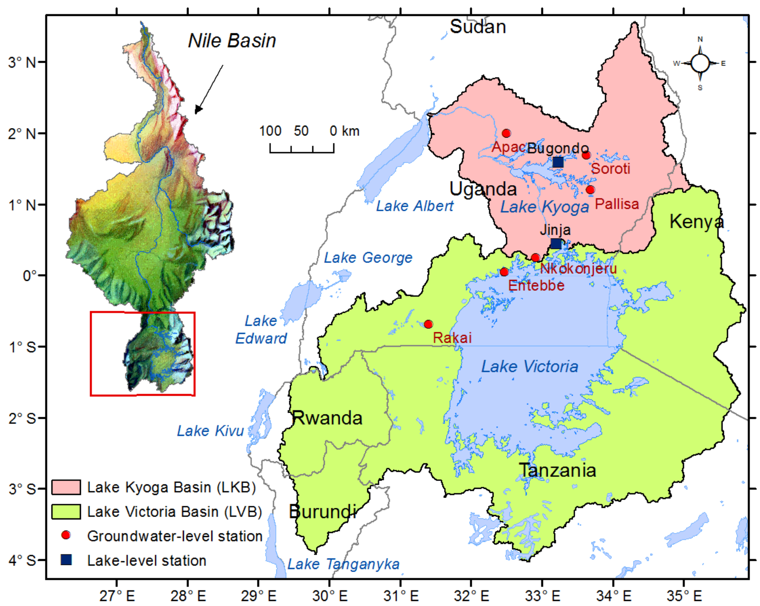

Figure 1. Map of the study area encompassing the Lake Victoria Basin (LVB) and Lake Kyoga Basin (LKB), and location of the in situ monitoring stations. The Upper Nile Basin is marked by a rectangle (red) within the entire Nile River Basin shown as a shaded relief index map. Piezometric monitoring (red circles) and lake-level gauging (dark blue squares) stations are shown on the map.

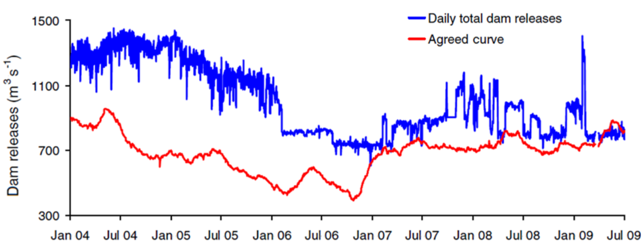

Figure 2. Observed daily total dam releases (blue line) and the agreed curve (red line) at the outlet of Lake Victoria in Jinja from November 2007 to July 2009 (Owor et al., 2011).

bined with simulated ΔSMS by the GLDAS LSMs, we assess (1) the ability of current gridded GRACE products (i.e. *GRCTellus*, JPL-Mascons, and GRGS GRACE) to measure a well-constrained ΔTWS in the Upper Nile Basin from 2003 to 2012, focusing on the unintended experiment within the LVB from 2003 to 2006; and (2) the sensitivity of disaggregated GRACE ΔTWS signals to trace ΔGWS in a deeply weathered crystalline rock aquifer system underlying the Upper Nile Basin.

2 The Upper Nile Basin

2.1 Hydroclimatology

The Upper Nile Basin, the headwater area of the ∼ 3 400 000 km^2 Nile Basin (Awange et al., 2014), includes both the LVB and LKB. Mean annual rainfall over the entire basin varies from 650 to 2900 mm (TRMM monthly rainfall; 2003–2012), with an average of 1300 mm and a standard deviation of 354 mm (Fig. 3). Mean annual gauged rainfall at different stations, Jinja, Bugondo, and Entebbe, measured 1195, 1004, and 1541 mm respectively (Owor et al., 2011). Rainfall over Lake Victoria is typically 25–30 % greater than that measured in the surrounding catchment (Fig. 3), which is partially explained by the nocturnal "lake breeze" effect (Yin and Nicholson, 1998; Nicholson et al., 2000; Owor et al., 2011).

Estimates of mean annual evaporation from the surface of Lake Victoria vary from 1260 mm (UNEP, 2013) to 1566 mm (Hoogeveen et al., 2015), whereas mean annual evaporation from the surface of Lake Kyoga is estimated to vary from 1205 mm (Brown and Sutcliffe, 2013) to 1660 mm (Hoogeveen et al., 2015). Evapotranspirative fluxes from the surrounding swamps in Lake Kyoga are estimated to be much higher and approximately 2230 mm yr^{-1} (Brown and Sutcliffe, 2013).

Annual rainfall is predominantly bimodal in distribution (Fig. 4), with two distinct rainy seasons driven by the movement of the Intertropical Convergence Zone (ITCZ) (Awange et al., 2013). Long rains (March–May) and short rains (September–November) account for approximately 40 and 25 % of annual rainfall respectively (Basalirwa, 1995; Indeje et al., 2000). The latter rainfalls are particularly influenced by the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). GRACE-derived ΔTWS within the LVB shows a statistical association (R^2) of 0.56 with ENSO and 0.48 with IOD (Awange et al., 2014).

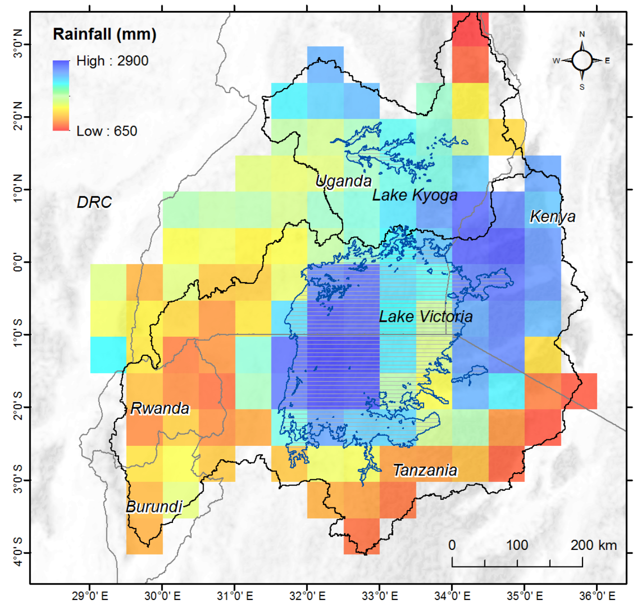

Figure 3. Mean annual rainfall for the period of 2003–2012 derived from TRMM satellite observations. Greater annual rainfall is observed over much of Lake Victoria and the north-eastern corner of the Lake Victoria Basin.

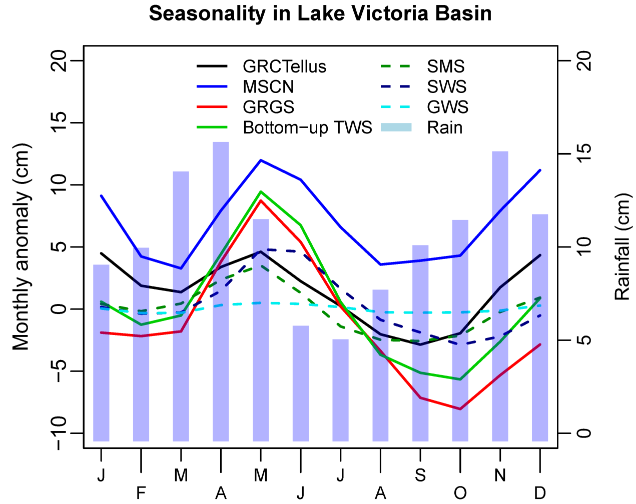

Figure 4. Seasonal pattern (monthly mean from January 2003 to December 2012) of TRMM-derived monthly rainfall, various GRACE-derived ΔTWS signals (GRCTellus: ensemble mean of CSR, JPL, and GFZ; GRGS and JPL-Mascons (MSCN) products), the bottom-up TWS, GLDAS LSM ensemble mean ΔSMS, in situ ΔSWS, and a borehole-derived estimate of ΔGWS over the Lake Victoria Basin.

2.2 Lakes Victoria and Kyoga

Located between the 31°39′ and 34°53′ E longitudes, and the 0°20′ N and 3°00′ S latitudes, Lake Victoria (Fig. 1) is located in Tanzania, Uganda, and Kenya, where each accounts for 51, 43, and 6 % of the lake surface area respectively (Kizza et al., 2012). Lake Victoria is relatively shallow, with a mean depth of ∼ 40 m and a maximum depth of 84 m (UNEP, 2013) akin to many shallow, open surface-water bodies as well as permanent and seasonal wetlands occupying low-relief plateaus across the Great Lakes Region of Africa (Owor et al., 2011). Moreover, the western and north-western lake bathymetry is characterized by even shallower depths of between 4 and 7 m (Owor, 2010). Hydrologically, lake input is dominated by direct rainfall (84 % of total input); the remainder derives primarily from river inflows as direct groundwater inflow (< 1 %) is negligible (Owor et al., 2011). Approximately 25 major rivers flow into Lake Victoria, with a total catchment area of ∼ 194 000 km^2; the largest tributary, the Kagera River, contributes ∼ 30 % of total river inflows (Sene and Plinston, 1994). Lake Victoria outflow to Lake Kyoga occurs at Jinja (Fig. 1).

Lake Kyoga (Fig. 1), located between the 32°10′ and 34°20′ E longitudes and the 1°00′ and 2°00′ N latitudes, has a mean area of 1720 km^2 with an estimated mean volume of 12 km^3 (Owor, 2010; UNEP, 2013). According to the recent global *HydroSHEDS* (Hydrological data and maps based on shuttle elevation derivatives at multiple scales) database, Lake Kyoga has a total surface area of 2729 km^2 (Lehner et al., 2008). Lake Kyoga comprises lake-zone and through-flow conduit areas. The lake zone in Lake Kyoga is very shallow, with a mean depth of 3.5–4.5 m (Owor, 2010). Lake Kyoga has a through-flow channel (mean depth 7–9 m) where the main Victoria Nile River flows (Owor, 2010) and acts as a linear reservoir with the annual water balance predominantly governed by the discharge of the Victoria Nile from Lake Victoria. Whilst numerous rivers flow into Lake Kyoga (e.g. rivers Mpologoma, Awoja, Omunyal, Abalang, Olweny, Sezibwa, and Enget), the majority contributes a fraction of their former volume upon reaching the lake (Krishnamurthy and Ibrahim, 1973) due, in part, to evapotranspirative losses from fringe swamp areas (4510 km^2) surrounding the lake (UNEP, 2013).

2.3 Hydrogeological setting

The Upper Nile Basin is underlain primarily by deeply weathered crystalline rock aquifer systems that have evolved through long-term, tectonically driven cycles of deep weathering and erosion (Taylor and Howard, 2000). Groundwater occurs within unconsolidated regoliths or "saprolite" and, below this, in fractured bedrock, known as "saprock". Bulk transmissivities of the saprolite and saprock aquifers are generally low (1–20 m^2 d^{-1}) (Taylor and Howard, 2000; Owor, 2010) and field estimates of the specific yield of the saprolite, the primary source of groundwater storage in these aquifer systems, are 2 % based on pumping tests with tracers (Taylor et al., 2010) and magnetic resonance sounding experiments (Vouillamoz et al., 2014). Borehole yields are highly variable

Table 1. Estimated areal extent (km^2) of the Lake Victoria Basin (LVB), the Lake Kyoga Basin (LKB), Lake Victoria, and Lake Kyoga.

Basin/lake	This study (*HydroSHEDS* database)	UNEP (2013)	Awange et al. (2014)
Lake Victoria Basin	256 100	184 000	258 000
Lake Victoria	67 220	68 800	–
Lake Kyoga Basin	79 270	75 000	75 000
Lake Kyoga	2730	1720	–

but generally low (0.5–20 $m^3 h^{-1}$), yet are of critical importance to the provision of safe drinking water.

2.4 An observed reduction in TWS in the LVB

In 1954, the construction of the Nalubaale Dam (formerly Owen Falls Dam) at the outlet of Lake Victoria at Jinja transformed the lake into a controlled reservoir (Sene and Plinston, 1994). Operated as a run-of-river hydroelectric project to mimic pre-dam outflows, the "agreed curve" between Uganda and Egypt dictated dam releases that were controlled on a 10-day basis and generally adhered to, with compensatory discharge releases to minimize any departures, until the construction of the Kiira Dam at Jinja in 2002 (Sene and Plinston, 1994; Owor et al., 2011).

The combined discharge of the Nalubaale and Kiira dams enabled total dam releases (Fig. 2) to substantially exceed the agreed curve (Sutcliffe and Petersen, 2007), and between May 2004 and February 2006 the lake level dropped by 1.2 m (equivalent ΔSWS loss of 81 km^3) (Owor et al., 2011). Mean annual releases were 1387 $m^3 s^{-1}$ (+162 % of the agreed curve) in 2004 and 1114 $m^3 s^{-1}$ (+148 % of the agreed curve) in 2005. Sharp reductions in dam releases in 2006 helped to arrest and reverse the lake-level decline, with lake levels stabilizing by early 2007.

3 Data and methods

3.1 Datasets

We use publicly available time-series records of (1) GRACE TWS solutions from a number of data-processing strategies and dissemination centres including NASA's *GRCTellus* land solutions (RL05 for CSR, GFZ, version DSTvSCS1409, RL05.1 for JPL; version DSTvSCS1411, and JPL-Mascons solution, version RL05M_1.MSCNv01) as well as the French National Centre for Space Studies (CNES) GRGS solution (version GRGS RL03-v1); (2) NASA's Global Land Data Assimilation System (GLDAS) simulated soil moisture data from three global land-surface models (LSMs) (CLM, NOAH, VIC); and (3) monthly precipitation data from NASA's Tropical Rainfall Measuring Mission (TRMM) satellite mission. We also employ in situ observations of lake levels and groundwater levels from a network of river gauges and monitoring boreholes operated by the Ministry of Water and Environment in Entebbe (Uganda). Datasets are briefly described below.

3.1.1 Delineation of basin study areas

Delineation of the LVB and LKB was conducted in a geographic information system (GIS) environment under an ArcGIS (v.10.3.1) environment using the Hydrological Basins in Africa datasets derived from the *HydroSHEDS* database (available at http://www.hydrosheds.org/) (Lehner et al., 2006, 2008). Regional water bodies, including lakes Victoria and Kyoga (Fig. 1), were spatially defined by the Inland Water dataset available globally at country scale from DIVA-GIS (http://www.diva-gis.org/). Computed areas of the basins and lake surface areas are summarized in Table 1 along with previously estimated figures from other studies.

3.1.2 GRACE-derived terrestrial water storage (TWS)

Twin GRACE satellites provide monthly gravity variations interpretable as ΔTWS (Tapley et al., 2004) with an accuracy of $\sim$ 1.5 cm (equivalent water thickness or depth) when spatially averaged (Wahr et al., 2006). In this study, we apply five different monthly GRACE solutions for the period of January 2003 to December 2012: post-processed, gridded (1° × 1°) GRACE-TWS time-series records from three *GRCTellus* land solutions from CSR, JPL, and GFZ processing centres (available at http://grace.jpl.nasa.gov/data) (Swenson and Wahr, 2006; Landerer and Swenson, 2012), JPL-Mascons (Watkins et al., 2015; Wiese et al., 2015), and GRGS GRACE products (CNES/GRGS release RL03-v1) (Biancale et al., 2006).

GRCTellus land solutions are post-processed from two versions, RL05 and RL05.1 of spherical harmonics released by the University of Texas at Austin Centre for Space Research (CSR), the German Research Centre for Geosciences Potsdam (GFZ), and NASA's Jet Propulsion Laboratory (JPL) respectively. *GRCTellus* gridded datasets are available at a monthly time step at a spatial resolution of 1° × 1° ($\sim$ 111 km at the Equator) though the actual spatial resolution of the GRACE footprint is $\sim$ 450 km or $\sim$ 200 000 km^2 (Scanlon et al., 2012). Post-processing of *GRCTellus* GRACE datasets primarily involve (i) removal of atmospheric pressure or mass changes based on the European Centre for Medium-Range Weather Forecasts (ECMWF) model; (ii) a glacial isostatic adjustment (GIA) correction based on a viscoelastic 3-D model of the Earth (A et al., 2013); and (iii) an application of a destriping filter plus a 300 km Gaussian to minimize the effect of correlated errors (i.e. destriping) manifested by N–S elongated stripes on GRACE monthly maps. However, the use of a large spatial filter and truncation of spherical harmonics leads to energy removal, so scaling coefficients or factors are applied to the *GRCTellus* GRACE-derived TWS data in order to restore attenuated signals (Landerer and Swenson, 2012). Dimensionless scaling factors are provided as $1° \times 1°$ bins (see Fig. S1 in the Supplement) that are derived from the Community Land Model (CLM4.0) (Landerer and Swenson, 2012).

JPL-Mascons (version RL05M_1.MSCNv01) data processing also involves a glacial isostatic adjustment (GIA) correction based on a viscoelastic 3-D model of the Earth (A et al., 2013). JPL-Mascons applies no spatial filtering as JPL-RL05M directly relates inter-satellite range-rate data to mass concentration blocks or Mascons to estimate global monthly gravity fields in terms of equal area $3° \times 3°$ mass concentration functions to minimize measurement errors. The use of Mascons and the special processing result in better signal-to-noise ratios of the Mascon fields compared to the conventional spherical harmonic solutions (Watkins et al., 2015). For convenience, gridded Mascon fields are provided at a spatial sampling of 0.5° in both latitude and longitude ($\sim$ 56 km at the Equator). As with *GRCTellus* GRACE datasets, the neighbouring grid cells are not "independent" of each other and cannot be interpreted individually at the 1° or 0.5° grid scale (Watkins et al., 2015). Similar to *GRCTellus* GRACE (CSR, JPL, GFZ) products, dimensionless scaling factors are provided as $0.5° \times 0.5°$ bins (see Fig. S2) that are also derived from the Community Land Model (CLM4.0) (Wiese et al., 2016). The gain factors or scaling coefficients are multiplicative factors that minimize the difference between the smoothed and unfiltered monthly ΔTWS variations from "actual" land hydrology at a given geographical location (Wiese et al., 2016).

GRGS/CNES GRACE monthly products (version RL03-v1) are processed and made publicly available (http://grgs.obs-mip.fr/grace) by the French Government space agency, National Centre for Space Studies or Centre National d' Études Spatiales (CNES). The post-processing of GRGS data involves taking into account of gravitational variations such as Earth tides, ocean tides, and 3-D gravitational potential of the atmosphere and ocean masses (Bruinsma et al., 2010). The remaining signals for time-varying gravity fields therefore represent changes in terrestrial hydrology including snow cover, baroclinic oceanic signals and effects of post-glacial rebound (Biancale et al., 2006; Lemoine et al., 2007). Further details on the Earth's mean gravity-field models can be found on the official website of GRGS/LAGEOS (http://grgs.obs-mip.fr/grace/).

GRACE satellites were launched in 2002 to map the variations in Earth's gravity field over its 5-year lifetime, but both satellites are still in operation even after more than 14 years. However, active battery management since 2011 has led the GRACE satellites to be switched off every 5–6 months for 4–5-week durations in order to extend its total lifespan (Tapley et al., 2015). As a result, GRACE ΔTWS time-series data have some missing records that are linearly interpolated (Shamsudduha et al., 2012). In this study, we derive ΔTWS time-series data as equivalent water depth (cm of H_2O) using the basin boundaries (GIS shapefiles) for masking the $1° \times 1°$ grids.

3.1.3 Rainfall data

We apply the Tropical Rainfall Measuring Mission (TRMM) (Huffman et al., 2007) monthly product (3B43 version 7) for the period of January 2003 to December 2012 at $0.25° \times 0.25°$ spatial resolution and aggregate to $1° \times 1°$ grids over the LVB and LKB. The general climatology of the Upper Nile Basin is represented by a long-term (2003–2012) mean annual rainfall (Fig. 3) and seasonal rainfall pattern (Fig. 4). TRMM rainfall measurements show a good agreement with limited observational precipitation records (Awange et al., 2008, 2014).

3.1.4 Soil moisture storage (SMS)

NASA's Global Land Data Assimilation System (GLDAS) is an uncoupled land-surface modelling system that drives multiple land surface models (GLDAS LSMs: CLM, NOAH, VIC and MOSAIC) globally at high spatial and temporal resolutions (3-hourly to monthly at $0.25° \times 0.25°$ grid resolution) and produces model results in near-real time (Rodell et al., 2004). These LSMs provide a number of output variables which include soil moisture storage (SMS). Similar to the approach applied in the analysis of GRACE-derived ΔTWS analysis in the Bengal Basin (Shamsudduha et al., 2012), we apply simulated monthly ΔSMS records at a spatial resolution of $1° \times 1°$ from three GLDAS LSMs: the Community Land Model (CLM, version 2) (Dai et al., 2003), NOAH (version 2.7.1) (Ek et al., 2003) and the Variable Infiltration Capacity (VIC) model (version 2.7.1) (Liang et al., 2003). The respective depths of modelled soil profiles are 3.4, 2.0, and 1.9 m in CLM (10 vertical layers), NOAH (4 vertical layers), and VIC (version 1.0) (3 vertical layers). Because of the absence of in situ soil moisture data in the study areas, we apply an ensemble mean of the aforementioned three LSMs-derived simulated ΔSMS time-series records (see Figs. 5 and 6) in order to disaggregate GRACE ΔTWS signals in the LVB and LKB.

3.1.5 Surface water storage (SWS)

Daily time series of ΔSWS are computed from in situ (gauged) lake-level observations at Jinja for Lake Victoria

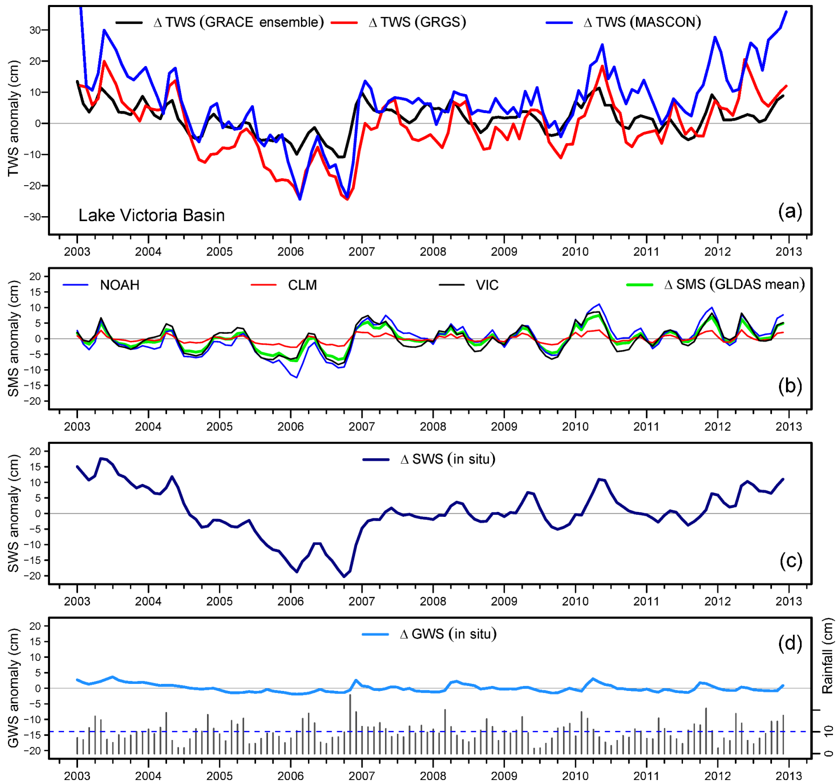

Figure 5. Monthly time-series datasets for the LVB from January 2003 to December 2012: **(a)** *GRCTellus* GRACE-derived ΔTWS (ensemble mean of CSR, GFZ, and JPL), GRGS and JPL-Mascons ΔTWS time-series data; **(b)** GLDAS-derived ΔSMS (individual signals as well as an ensemble mean of NOAH, CLM, and VIC); **(c)** lake-level-derived ΔSWS; and **(d)** borehole-derived ΔGWS time-series data. Note that monthly rainfall records derived from TRMM satellite are plotted on panel **(d)** where the dashed horizontal line represents the mean monthly rainfall for the period of January 2003 to December 2012.

and Bugondo for Lake Kyoga (Figs. 1 and 2) compiled by the Ugandan Ministry of Water and Environment (Directorate of Water Resources Management). Mean monthly anomalies for the period of January 2003–December 2012 were computed as an equivalent water depth using Eq. (2). Missing data in the time series (2003–2012) records are linearly interpolated. For instance, in the case of monthly ΔSWS derived from Lake Kyoga water levels, there is one missing record (December 2005).

$$\Delta \text{SWS} = \Delta \text{Lake level} \cdot \left(\frac{\text{Lake area}}{\text{Total basin area}} \right) \tag{2}$$

3.1.6 Groundwater storage (GWS) from borehole observations

Time series of ΔGWS are constructed from in situ piezometric records from 6 monitoring wells located in the LVB and LKB where near-continuous, daily observations exist from January 2003 to December 2012 and have been compiled by the Ugandan Ministry of Water and Environment (Directorate of Water Resources Management) (Owor et al., 2009, 2011). Monitoring boreholes were installed into weathered, crystalline rock aquifers that underlie much of the LVB and LKB, and are remote from local abstraction. As such, they represent variations in groundwater storage influenced primarily by climate variability. Mean monthly anomalies of ΔGWS, standardized to mean records from January 2003 to December 2012, were derived from near-continuous, daily observations at Entebbe, Rakai, and Nkokonjeru for the LVB and at Apac, Pallisa, and Soroti for the LKB (Figs. 1 and S3; Table 2). In the Lake Kyoga Basin, piezometric records from three sites show consistency in the seasonality and amplitude of groundwater storage changes plotted as monthly groundwater-level anomalies relative to the mean for the period from January 2003 to December 2012. In the Lake Victoria Basin, groundwater-level records from two sites (Entebbe, Nkokonjeru) are similar in their phase and amplitude, and are influenced by changes in the level of Lake Victoria as demonstrated by Owor et al. (2011). The groundwater-level record from Rakai represents local semi-arid conditions that exist within catchment areas (e.g. the Ruizi River) draining to the western shore of Lake Victoria in Uganda. Although there are differences in the phase of groundwater-level fluctuations between the semi-arid site at Rakai and both Entebbe

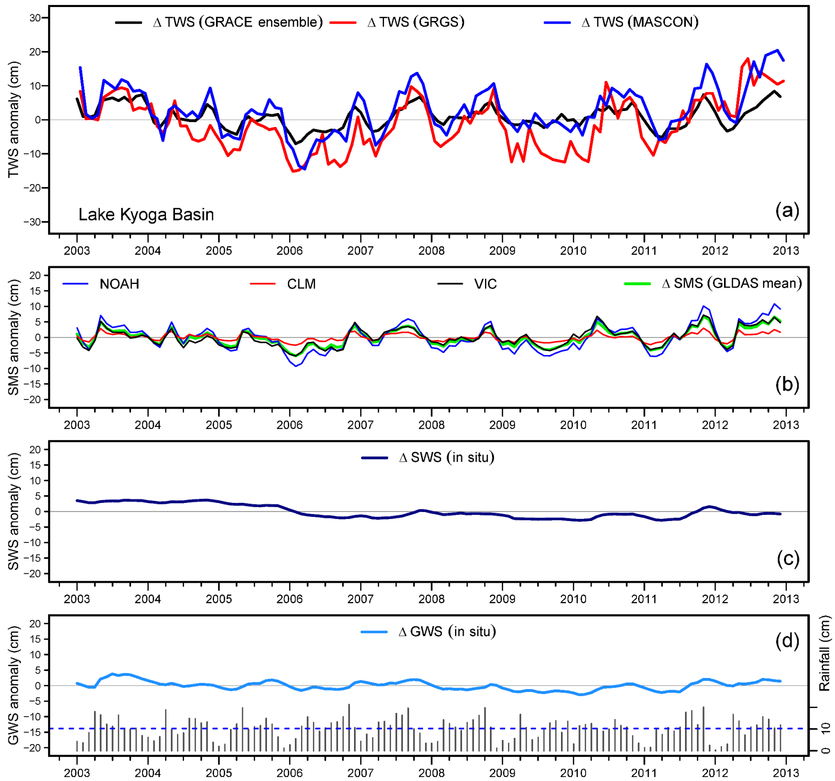

Figure 6. Monthly time-series datasets for the Lake Kyoga Basin (LKB) from January 2003 to December 2012: **(a)** *GRCTellus* GRACE-derived ΔTWS (ensemble mean of CSR, GFZ, and JPL), GRGS, and JPL-Mascons ΔTWS time-series data; **(b)** GLDAS-derived ΔSMS (individual signals as well as an ensemble mean of NOAH, CLM, and VIC); **(c)** lake-level-derived ΔSWS; and **(d)** borehole-derived ΔGWS time-series data. Note that monthly rainfall records derived from the TRMM satellite are plotted in panel **(d)** where the dashed horizontal line represents the mean monthly rainfall for the period of January 2003 to December 2012.

Table 2. Details of groundwater and lake-level monitoring stations located in the Lake Victoria Basin and Lake Kyoga Basin.

Monitoring station	Basin	Parameter	Longitude	Latitude	Depth (m b.g.l.)
Apac	LKB	Groundwater level	32.50	1.99	15.0
Pallisa	LKB	Groundwater level	33.69	1.20	46.2
Soroti	LKB	Groundwater level	33.63	1.69	66.0
Bugondo	LKB	Lake level	33.20	0.45	–
Entebbe	LVB	Groundwater level	32.47	0.04	48.0
Rakai	LVB	Groundwater level	31.40	−0.69	53.0
Nkokonjeru	LVB	Groundwater level	32.91	0.24	30.0
Jinja	LVB	Lake level	33.23	1.59	–

and Nkokonjeru (as well as the three sites in the Lake Kyoga Basin), annual amplitudes are similar.

The groundwater-level time series data are a sub-set of the total number of available monitoring-well records in the LVB and LKB and selected on the basis of (i) the completeness and quality of the records from 2003 to 2012, and (ii) rigorous review of groundwater-level records conducted at a dedicated workshop at the Ministry of Water & Environment in January 2013. These records represent shallow groundwater-level observations within the saprolite that is dynamically connected to surface waters (Owor et al., 2011). Long time-series records of groundwater levels over the period from 2003 to 2012 from western Kenya, northern Tanzania, Rwanda, and Burundi have not been identified despite intensive investigations carried out by *The Chronicles Consortium*.[1] The partial spatial coverage in quality-controlled piezometry, especially for the LVB, represents an important limitation in our analysis.

[1]The Chronicles Consortium: https://www.un-igrac.org/special-project/chronicles-consortium

Mean monthly anomalies were translated into an equivalent water depth (Eq. 3) by applying a range of specific yield (S_y) values (1–6 % with an average of 3 %), although estimates of S_y in hard-rock environments are observed to vary from < 2 to 8 % (Taylor et al., 2010, 2013; Vouillamoz et al., 2014) using Eq. (3). Missing data in the time series were linearly interpolated. In the case of monthly ΔGWS that were derived from borehole ($n = 6$) observations, missing records range from 1 to 9 months (120 months in 2003–2012), with three boreholes (Soroti, Rakai, and Nkonkonjero) with time-series records ending in June–July 2010.

$$\Delta\mathrm{GWS} = \Delta h \cdot S_y \cdot \left(\frac{\text{Land area}}{\text{Total basin area}}\right) \quad (3)$$

3.2 Methodologies

3.2.1 GRACE ΔTWS estimation

First, the $1° \times 1°$ gridded monthly anomalies of GRACE-derived ΔTWS and GLDAS LSM-derived ΔSMS are masked over the area of the LVB and LKB. GRACE ΔTWS along with GLDAS ΔSMS are extracted for the marked $1° \times 1°$ grid cells for the LVB and LKB and the grid values are spatially aggregated to form time series of monthly anomalies ΔTWS and ΔSMS.

GRCTellus GRACE ΔTWS gridded data are scaled using dimensionless, gridded scaling factors. Several GRACE studies (Rodell et al., 2009; Sun et al., 2010; Shamsudduha et al., 2012) have applied scaling factors in three different ways: (1) a single scaling factor based on regionally averaged time series, (2) spatially distributed or gridded scaling factors based on time series at each grid point, and (3) gridded-gain factors estimated as a function of time or of temporal frequency (Landerer and Swenson, 2012; Long et al., 2015). In this study, we apply a spatially distributed scaling approach (method 2 above) to generate basin-averaged ΔTWS time-series records for *GRCTellus* (CSR, JPL, GFZ) products. Scaling factors provided at $1° \times 1°$ grids are applied to each corresponding GRACE ΔTWS grid for NASA's *GRCTellus* products in order to restore attenuated signals during the post-processing (Landerer and Swenson, 2012) using Eq. (4). Similarly, provided scaling factors are applied to JPL-Mascons ΔTWS time-series data but at $0.5° \times 0.5°$ grid resolution. No scaling factors were applied to GRGS GRACE ΔTWS as the monthly gravity solutions have already been stabilized during their generation process.

$$g^1(x, y, t) = g(x, y, t) \cdot s(x, y) \quad (4)$$

Here, $g^1(x, y, t)$ represents each un-scaled grid where x represents longitude, y represents latitude, t represents time (month), and $s(x, y)$ is the corresponding scaling factor.

For the three *GRCTellus* gridded products (i.e. CSR, GFZ, and JPL solutions), we apply an ensemble mean of scaled GRACE ΔTWS as our exploratory analyses reveal that ΔTWS time-series records over the Lake Victoria Basin are highly correlated ($r > 0.95$, p value < 0.001) with each other. Additionally, a small (ranges from 1.3 to 1.9 cm) root mean square error (RMSE) among the GRACE ΔTWS datasets suggests substantial similarities in phase and amplitude.

3.2.2 Estimation of ΔGWS from GRACE

Estimation of groundwater storage changes (ΔGWS) from GRACE measurements is conducted using Eq. (5) in which $\Delta\mathrm{TWS}_t$ is derived from gridded GRACE products (spatially scaled ΔTWS for *GRCTellus* and JPL-Mascons but unscaled ΔTWS for GRGS), $\Delta\mathrm{SMS}_t$ is an ensemble mean of three GLDAS LSMs (CLM, NOAH, VIC), and $\Delta\mathrm{SWS}_t$ is area-weighted, in situ surface water storage estimated from lake-level records using Eq. (2).

$$\Delta\mathrm{GWS}_t = \Delta\mathrm{TWS}_t - (\Delta\mathrm{SWS}_t + \Delta\mathrm{SMS}_t) \quad (5)$$

3.2.3 Reconciliation of GRACE ΔTWS disaggregation

Reconciling GRACE-derived TWS with ground-based observations is limited by the paucity of in situ observations of SMS, SWS, and GWS in many environments. In addition, direct comparisons between in situ observations of ΔSMS, ΔSWS, and ΔGWS and gridded GRACE ΔTWS anomalies are complicated by substantial differences in spatial scales, which need to be considered prior to analysis (Becker et al., 2010). For example, individual groundwater-level monitoring boreholes may represent, depending on borehole depth, a sensing area of several tens of square kilometres (Burgess et al., 2017), whereas the typical GRACE footprint is $\sim 200\,000\,\mathrm{km}^2$. The disaggregation of GRACE ΔTWS into individual water stores can also propagate errors to disaggregated components. Here, we construct "in situ" or "bottom-up" ΔTWS (i.e. combined signals of ΔSMS, ΔSWS, and ΔGWS) for the Lake Victoria Basin and attempt to reconcile with GRACE-derived ΔTWS. One feature of GRACE ΔTWS among the three solutions we apply in this study is the considerable variation in annual amplitudes that exist over the period of 2003–2012.

In addition, for the *GRCTellus* products, we conduct unconventional scaling experiments, outlined below in an attempt to reconcile satellite and in situ measures and to shed light on the uncertainty in ΔTWS amplitudes of the *GRCTellus* GRACE products. The ΔTWS signals in CSR, JPL, and GFZ products are greatly attenuated due to spatial smoothing and the amplitude is substantially smaller compared to JPL-Mascons and GRGS products. In the first scaling experiment, we apply an additional, basin-averaged, multiplicative scaling factor to ΔTWS ranging from 1.1 to 2.0 and employ RMSE to assess their relative performance. With reference to the *GRCTellus* GRACE ΔTWS and bottom-up ΔTWS relationship, the scaling factor producing the lowest RMSE between the two time series is employed. Secondly, it is observed that, in the LVB, ΔSWS is the largest contributor, representing ∼ 50 % variance in the in situ or bottom-up ΔTWS time-series signal. GRACE ΔTWS analyses commonly apply the same scaling factor as ΔTWS to all other individual components (Landerer and Swenson, 2012). Therefore, under the scaling experiment, we apply to in situ ΔSWS spatially averaged scaling factors representative of (i) Lake Victoria and its surrounding grid cells (experiment 1: $s = 0.71$; range 0.02–1.5), and (ii) the open-water surface of Lake Victoria without surrounding grid cells (experiment 2: $s = 0.11$; range 0.02–0.30). Furthermore, we find that the amplitude of monthly anomalies of ΔSWS + ΔSMS combined substantially exceed ΔTWS (see Fig. S4), particularly for the *GRCTellus* GRACE ΔTWS signal that is greatly smoothed due to filtering. This discrepancy is pronounced over the period of 2003–2006, and when applied to estimate GRACE-derived ΔGWS, produces steep, rising trends in the estimated ΔGWS (i.e. GRACE ΔTWS − (ΔSWS + ΔSMS)), whereas borehole observations of groundwater levels show a declining trend and are of much a lower amplitude over the same period.

4 Results

Monthly time-series records (January 2003–December 2012) are presented in Figs. 5 and 6 respectively for the LVB and LKB of (a) GRACE ΔTWS from *GRCTellus* GRACE ΔTWS (ensemble mean of CSR, GFZ, and JPL solutions), GRGS and JPL-Mascons, (b) GLDAS land-surface models (LSMs) derived ΔSMS (ensemble mean of three LSMs: NOAH, CLM, VIC), (c) in situ ΔSWS from lake levels records, and (d) in situ ΔGWS borehole observations. Monthly rainfall derived from TRMM satellite observations over the same period are shown on the bottom panel (d). Time-series records of all ΔTWS components and rainfall are aggregated for the LVB to represent the average seasonal (monthly) pattern of each signal (Fig. 4) that shows an obvious lag (∼ 1 month) between peak rainfall (March–April) and ΔTWS and its individual components.

Mean annual (2003–2012) amplitudes of various GRACE-derived ΔTWS signals, bottom-up ΔTWS, ensemble mean of simulated ΔSMS, in situ ΔSWS, and ΔGWS time-series records (Figs. 5 and 6) are presented (see Table S1 in the Supplement) for both the LVB and LKB. The mean annual amplitude of GRACE ΔTWS ranges from 11 to 21 cm among *GRCTellus*, GRGS, and JPL-Mascons GRACE products in the LVB, and from 8.4 to 16.4 respectively in the LKB. The mean annual amplitude of in situ ΔSWS is much greater (14.8 cm) in the LVB than in the LKB (3.8 cm). The GLDAS LSM-derived ensemble mean ΔSMS amplitude in the LVB is 7.9 and 7.3 cm in the LKB. The standard deviation in ΔSMS varies substantially in the LVB (1.2, 4.2, and 2.9 cm) and LKB (1.3, 4.7, and 4.0 cm) for the CLM, NOAH, and VIC models respectively. The mean annual amplitude of in situ ΔGWS ranges from 4.4 cm (LVB) to 3.5 cm (LKB).

Time-series correlation (Pearson) analysis over various periods of interests (decadal: 2003–2012; well-constrained SWS reduction or the period of the unintended experiment: 2003–2006; controlled dam operation: 2007–2012) reveals that GRACE-derived ΔTWS signals are strongly correlated in both the LVB and LKB (see Figs. S5–S10). For example, in the LVB, in situ ΔSWS shows a statistically significant (p value < 0.001) strong correlation ($r = 0.77$–0.92) with all GRACE-ΔTWS time-series (2003–2012) records. Similarly, simulated ΔSMS shows statistically significant (p value < 0.001) strong correlation ($r = 0.70$–0.78) with ΔTWS time-series records. In contrast, in situ ΔGWS shows statistically significant (p value < 0.001) but moderate correlation ($r =0.63$–0.69) with ΔTWS time-series records. Correlation among the variables shows similar statistically significant (p value < 0.001) but wide-ranging associations for the periods of the unintended experiment (2003–2006) and controlled dam operation (2007–2012). In the LKB, however, correlation among in situ ΔSWS and GRACE ΔTWS time-series records is statistically significant (p value < 0.05) but poor in correlation strength ($r = 0.22$–0.34). In situ ΔGWS shows statistically significant (p value < 0.001) strong correlation ($r = 0.64$–0.69) with GRACE ΔTWS time-series records.

Time-series records of all three ΔTWS from five GRACE products and bottom-up ΔTWS time-series records in both the LVB and LKB are shown in Fig. 7; results of temporal trends are summarized in Table 3. Statistically significant (p value < 0.05) declining trends (−4.1 to −11.0 cm yr^{-1} in the LVB; −2.1 to −4.6 cm yr^{-1} in the LKB) are consistently observed during the period of 2003–2006. Trends are all positive in GRACE ΔTWS and bottom-up ΔTWS time-series records over the recent period of controlled dam operation (2007–2012) in both the LVB and LKB. The overall, decadal (2003–2012) trends are slightly rising (0.04–1.00 cm yr^{-1}) in the LVB but nearly stable (−0.01 cm yr^{-1}) in *GRCTellus* ΔTWS and slightly declining (−0.56 cm yr^{-1}) in bottom-up ΔTWS over the LKB. In addition, short-term volumetric trends (2003–2006) in GRACE and bottom-up ΔTWS as well as simulated ΔSMS and in situ ΔSWS are declining whereas in situ ΔGWS and rainfall anomalies show slightly rising trends over the same period in the LVB (see Figs. S11–S12). Similar trends are reported in various signals over the LKB, but magnitudes are much smaller compared to that of the LVB, which is 3 times larger in size than the LKB. Volumetric declines in ΔTWS in the LVB for the period 2003–2006 are: 83 km^3 (bottom-up), 80 km^3 (JPL-Mascons), 69 km^3 (GRGS) and 31 km^3 (*GRCTellus* ensemble mean of CSR, JPL and GFZ products).

Linear regression reveals that the association between GRACE-derived ΔTWS and bottom-up ΔTWS is stronger in the LVB ($R^2 = 0.75$–0.90) than in the LKB ($R^2 = 0.56$–0.62) (see Table S1). GRACE ΔTWS is unable to explain

Table 3. Linear trends (cm yr^{-1}) in GRACE ΔTWS and bottom-up ΔTWS in the Lake Victoria Basin and Lake Kyoga Basin over various time periods (statistically significant trends; p values < 0.05 are marked by an asterisk).

Period	GRACE ensemble	GRGS	JPL-Mascons	Bottom-up TWS
Lake Victoria Basin (LVB)				
2003–2006	−4.10*	−9.00*	−10.0*	−11.00*
2007–2012	−0.31	1.50*	2.70*	1.10*
2003–2012	0.04	0.58	1.00*	0.54
Lake Kyoga Basin (LKB)				
2003–2006	−2.10*	−4.60*	−3.50*	−2.80*
2007–2012	0.22	2.00*	1.50*	0.48
2003–2012	−0.01	0.54*	0.54*	−0.56*

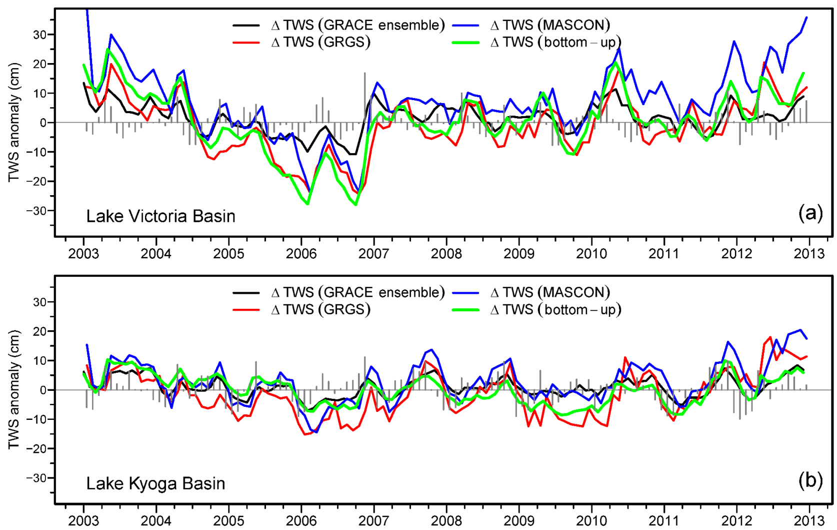

Figure 7. Comparison among time-series records of ΔTWS from *GRCTellus* (ensemble mean of CSR, GFZ, and JPL), GRGS and JPL-Mascons GRACE products and bottom-up ΔTWS for the LVB **(a)**, and the LKB **(b)** for the period of January 2003 to December 2012. The vertical grey lines represent monthly rainfall anomalies in the LVB and LKB.

natural variability in bottom-up ΔTWS in the LKB, though this may be explained by the fact that SWS in Lake Kyoga is influenced by dam releases from the LVB. Multiple linear regression and the analysis of variance (ANOVA) reveal that the relative proportion of variability in the bottom-up ΔTWS time-series record can be explained by ΔSWS (92.6 %), ΔSMS (6.5 %), and ΔGWS (0.66 %) in the LVB; and by 47.9, 48.5, and 3.6 % respectively in the LKB. These results are indicative only as these percentages can be biased by the presence of strong correlation among variables and the order of these variables listed as predictors in the multiple linear regression models.

Disaggregation of ΔGWS from GRACE ΔTWS time-series record from each product has been carefully considered and estimated following Eq. (5). No further additional scaling factors, as described in the “scaling experiment” section (see results of scaling experiment in Fig. S13) are applied in the final disaggregation of ΔGWS from GRACE ΔTWS signals. Results of Pearson correlation analysis of the time-series record (2003–2012) of in situ ΔGWS in the LVB show statistically insignificant and poor correlation ($r = 0.11$, p value = 0.25) to JPL-Mascons and an inverse correlation with both the ensemble *GRCTellus* ($r = -0.55$, p value < 0.001) and GRGS ($r = -0.27$, p value = 0.003) GRACE-derived estimates of ΔGWS (Fig. 8). In contrast, in the LKB, in situ ΔGWS time-series record shows statistically significant but weak correlations to JPL-Mascons ($r = 0.34$, p value < 0.001) and GRGS ($r = 0.39$, p value < 0.001) GRACE-derived ΔGWS but shows an inverse correlation ($r = -0.21$, p value = 0.02) to *GRCTellus* ΔGWS (see Fig. S14). Furthermore, RMSE among various GRACE-derived estimates of ΔGWS and in situ ΔGWS ranges from 7.2 cm (GRACE ensemble), 3.8 cm (GRGS) to 8.2 cm (JPL-Mascons) in the LVB, and from

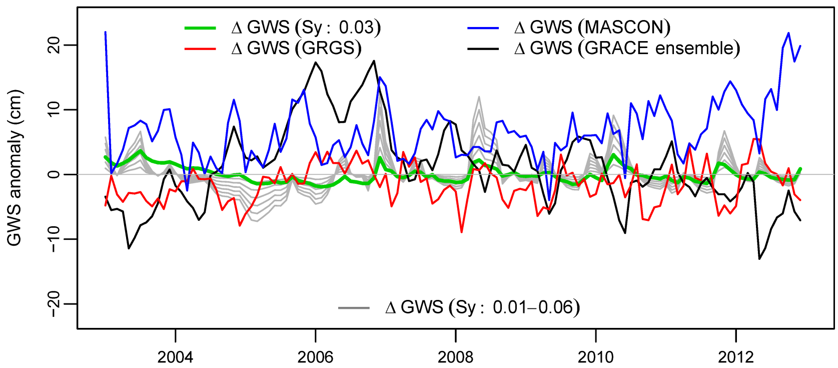

Figure 8. Estimates of in situ ΔGWS and GRACE-derived ΔGWS time-series records (January 2003 to December 2012) in the LVB show substantial variations among themselves. An ensemble mean ΔSMS (three GLDAS LSMs: CLM, NOAH, and VIC) and an unscaled ΔSWS are applied in the disaggregation of ΔGWS using the *GRCTellus* GRACE (ensemble mean of CSR, GFZ, and JPL) and JPL-Mascons products.

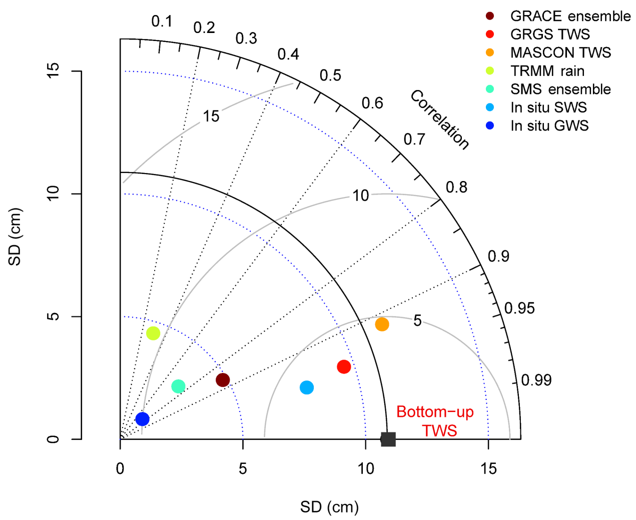

Figure 9. Taylor diagram shows strength of statistical association, variability in amplitudes of time-series records and agreement among the reference data, bottom-up ΔTWS and *GRCTellus* GRACE-derived ΔTWS (ensemble mean of CSR, GFZ, and JPL, GRGS and JPL-Mascons ΔTWS time-series records), simulated ΔSMS (ensemble mean of NOAH, CLM and VIC), in situ ΔSWS, and in situ ΔGWS over the LVB. The solid arcs around the reference point (black square) indicate centred root mean square (RMS) differences among bottom-up ΔTWS and other variables, and the dashed arcs from the origin of the diagram indicate variability in time-series records. Data for the LVB are only shown in this diagram.

3.2 cm (GRACE ensemble), 5.3 cm (GRGS) to 5.4 cm (JPL-Mascons) in the LKB.

5 Discussion

We apply five different gridded GRACE products (*GRCTellus* – CSR, JPL, and GFZ; GRGS and JPL-Mascons) to test ΔTWS signals for the Lake Victoria Basin (LVB) comprising a large and accurately observed reduction (83 km^3) in ΔTWS from 2003 to 2006. Our analysis reveals that all GRACE products capture this substantial reduction in terrestrial water mass, but the magnitude of GRACE ΔTWS among GRACE products varies substantially. For example, *GRCTellus* underrepresents greatly (63 %) the reduction of 83 km^3 in bottom-up ΔTWS, whereas GRGS and JPL-Mascons GRACE products underrepresent this by 17 and 4 % respectively. Previous studies in the Upper Nile Basin have relied upon a single GRACE product such as *GRCTellus* CSR (Nanteza et al., 2016) and GFZ (version (RL04) (Awange et al., 2014) without considering uncertainty in the seasonal amplitude of TWS associated with the processing of different GRACE products. Over a longer period (2003–2012) in the Upper Nile Basin, all GRACE products correlate well with bottom-up ΔTWS but, similar to the unintended experiment, variability in amplitude is considerable (Fig. 9). The average (2003–2012) annual amplitude of ΔTWS is substantially dampened (i.e. 45 % less than bottom-up ΔTWS) in *GRCTellus* GRACE products relative to GRGS (4 %) and JPL-Mascons (27 % more than bottom-up ΔTWS) products in the LVB.

The "true" amplitude in the *GRCTellus* ΔTWS signal is generally reduced during the post-processing of GRACE spherical harmonic fields, primarily due to spatial smoothing by a large-scale (e.g. 300 km) Gaussian filter and truncation of gravity fields at a higher (degree 60 = 300 km) spectral degree (Swenson and Wahr, 2006; Landerer and Swenson, 2012). Despite the application of scaling factors based on CLM v.4.0 to amplify *GRCTellus* ΔTWS amplitudes at individual grids, the basin-averaged (LVB) time-series record represents only 75 % variability in bottom-up ΔTWS.

Scaling experiments conducted here reveal that *GRCTellus* ΔTWS requires an additional multiplicative factor of 1.7 in order to match bottom-up ΔTWS with a minimum RMSE (5.8 cm). On the other hand, NASA's new gridded GRACE product, JPL-Mascons, which applies an a priori constraint in space and time to derive monthly gravity fields and undergoes some degree of spatial smoothing (Watkins et al., 2015), represents nearly 83 % variability in bottom-up ΔTWS. In contrast, the GRGS GRACE product, which applies truncation at degree 80 ($\sim$ 250 km), does not suffer from any large-scale spatial smoothing, and is able to represent well (90 %) the variability in bottom-up ΔTWS in the LVB.

A priori corrections of *GRCTellus* ensemble mean GRACE signals using a set of LSM-derived scaling factors (i.e. amplitude gain) can lead to substantial uncertainty in ΔTWS (Long et al., 2015). We show that the amplitude of simulated terrestrial water mass over the Upper Nile Basin varies substantially among various LSMs (see Fig. S15). Most of these LSMs (GLDAS models: CLM, NOAH, VIC) do not include surface water or groundwater storage (Scanlon et al., 2012). Although CLM (v.4.0 and 4.5) includes a simple representation (i.e. shallow unconfined aquifer) of groundwater (Niu et al., 2007; Oleson et al., 2008), it does not consider recharge from irrigation return flows. In addition, many of these LSMs do not consider lakes and reservoirs and, most critically, LSMs are not reconciled with in situ observations.

The combined measurement and leakage errors, $\sqrt{(\text{bias}^2 + \text{leak}^2)}$ (Swenson and Wahr, 2006) for *GRCTellus* ΔTWS based on CLM4.0 model for the LVB and LKB are 7.2 and 6.6 cm respectively. These values, however, do not represent mass leakage from the lake to the surrounding area within the basin itself. A sensitivity analysis of *GRCTellus* and GRGS signals reveal that signal leakage occurs from lake to its surrounding basin area as well as between basins. For instance, GRACE signal leakage into the LKB from the LVB, which is 3 times larger in area than the LKB, is 3.4 times bigger for both GRCTellus GRACE and GRGS products. Furthermore, the analysis shows that leakage from Lake Victoria to the LVB for *GRCTellus* is substantially greater than GRGS product by a factor of $\sim$ 2.6. In other words, 1 mm change in the level of Lake Victoria represents an equivalent change of 0.12 mm in ΔTWS in the LVB for *GRCTellus* compared to 0.32 mm for GRGS. Consequently, changes in the amplitude of GRGS ΔTWS are much greater ($\sim$ 38 %) than *GRCTellus.* During the observed reduction in ΔTWS (83 km^3) from 2003 to 2006, the computed volumetric reduction for GRGS is found to be 69 km^3 whereas it is 31 km^3 for *GRCTellus*.

Another source of uncertainty that contributes toward ΔTWS anomalies in GRACE analysis is the choice of simulated ΔSMS from various global-scale LSMs (e.g. Shamsudduha et al., 2012; Scanlon et al., 2015). For example, the mean annual (2003–2012) amplitudes in simulated ΔSMS in GLDAS LSMs (CLM, NOAH, VIC) vary substantially in the LVB (3.5, 10.2, and 10.5 cm) and LKB (3.7, 10.6, and 7.7 cm) respectively. Due to an absence of a dedicated monitoring network for soil moisture in the Upper Nile Basin, this study, like many other GRACE studies, is resigned to applying simulated ΔSMS from multiple LSMs, arguing that the use of an ensemble mean minimizes the error associated with ΔSMS (Rodell et al., 2009).

Computed contributions of ΔGWS to ΔTWS in the Upper Nile Basin are low ($<$ 10 %). GRACE-derived estimates of ΔGWS from all three products (*GRCTellus*, GRGS, and JPL-Mascons) correlate very weakly with in situ ΔGWS in both the LVB and LKB. One curious observation in the LVB during the unintended experiment (2003–2006) is that in situ ΔGWS rises, whereas in situ ΔSWS and simulated ΔSMS decline. The available evidence in groundwater-level records (e.g. Entebbe, Uganda) suggests that rainfall-generated groundwater recharge led to an increase in ΔGWS, while dam releases exceeding the agreed curve continued to reduce ΔSWS (Owor et al., 2011).

Uncertainties in the estimation of GRACE-derived ΔGWS remain in (i) accurate representation of the largest individual signal of in situ ΔSWS in the disaggregation of GRACE ΔTWS signals as it can limit the propagation of uncertainty in simulated ΔSMS, (ii) simulated ΔSMS by GLDAS land-surface models, (iii) the very limited spatial coverage in piezometry to represent in situ ΔGWS, and (iv) applied S_y (3 % with a range from 1 to 6 %) to convert in situ groundwater levels to ΔGWS. The lack of any strong correlation in GRACE-derived ΔGWS and in situ ΔGWS time-series records indicates that the magnitude of uncertainty is larger than the overall variability in ΔGWS in low-storage, low-transmissivity weathered crystalline aquifers within the Upper Nile Basin. Furthermore, statistically significant but negative correlations in both the LVB and LKB arise from a positive change in GRACE-derived ΔGWS when in situ ΔGWS is declining (e.g. 2003–2006 in the LVB; 2008–2010 in the LKB). This inconsistency suggests that the "true" GRACE ΔTWS signal is weakened during processing and that the combined ΔSWS + ΔSMS signal is greater than ΔTWS, mathematically resulting in a positive estimate of ΔGWS. In contrast to the assertions of Nanteza et al. (2016), applying the *GRCTellus* CSR solution, we find that this uncertainty prevents robust resolution of ΔGWS from GRACE ΔTWS in these complex hydrogeological environments of eastern Africa. Despite substantial efforts to improve groundwater-level monitoring and to collate existing groundwater-level records across Africa, we recognize that understanding of in situ ΔGWS remains greatly constrained by limitations in current observational networks and records. Since present uncertainties and limitations identified in the Upper Nile Basin occur in many of the weathered hard-rock aquifer environments that underlie 40 % of sub-Saharan Africa (MacDonald et al., 2012), tracing of ΔGWS using GRACE in these areas is unlikely to be robust until these uncertainties and limitations are better constrained.

6 Conclusions

The analysis of a large, accurately recorded reduction of 1.2 m in the water level of Lake Victoria, equivalent to a ΔSWS decline of 81 km^3 from 2004 to 2006, exposes substantial variability among five commonly used gridded GRACE products (*GRCTellus* CSR, JPL, GFZ; GRGS; JPL-Mascons) to quantify the amplitude of changes in terrestrial water storage (ΔTWS). Around this event, we estimate an overall decline in "in situ" or "bottom-up" ΔTWS (i.e. in situ ΔSWS and ΔGWS; simulated ΔSMS) over the LVB of 83 km^3 from 2003 to 2006. This value compares favourably with JPL-Mascons GRACE ΔTWS (80 km^3), is underrepresented by GRGS GRACE ΔTWS (69 km^3), and is substantially underrepresented by the ensemble mean of *GRCTellus* GRACE ΔTWS (31 km^3). Attempts to better reconcile *GRCTellus* GRACE ΔTWS to bottom-up ΔTWS through scaling techniques are unable to represent adequately the observed amplitude in ΔTWS but highlight the uncertainty in the amplitude of gridded GRACE ΔTWS datasets generated by various processing strategies.

From 2003 to 2012, GRGS, JPL-Mascons, and *GRCTellus* GRACE products trace well the phase in bottom-up ΔTWS in the Upper Nile Basin that comprises both the LVB and the LKB. In the LVB, for example, each explains 90 % (GRGS), 83 % (JPL-Mascons), and 75 % (*GRCTellus* ensemble mean of CSR, JPL, and GFZ) of the variance respectively in bottom-up ΔTWS. The relative proportion of variability in bottom-up ΔTWS (variance 120 cm^2 LVB, 24 cm^2 LKB) is explained by in situ ΔSWS (93 % LVB; 49 % LKB), GLDAS ensemble mean ΔSMS (6 % LVB; 48 % LKB), and in situ ΔGWS (∼ 1 % LVB; 4 % LKB); these percentages are indicative and can vary as individual TWS components are strongly correlated and the order of explanatory variables in the regression equation can affect the analysis of variance (ANOVA). In situ ΔGWS contributes minimally to ΔTWS and is only moderately associated with GRACE ΔTWS (strongest correlation of $r = 0.39$, p value < 0.001). The resolution of ΔGWS from GRACE ΔTWS in the Upper Nile Basin relies upon robust measures of ΔSWS and ΔSMS; the former is observed in situ, whereas the latter is limited by uncertainty in simulated ΔSMS, represented here and in many GRACE studies by an ensemble mean of GLDAS LSMs. Mean annual amplitudes in observed ΔGWS (2003–2012) from limited piezometry for the low-storage and low-transmissivity aquifers in deeply weathered crystalline rocks that underlie the Upper Nile Basin are small (1.8–4.9 cm for $S_y = 0.03$) and, given the current uncertainty in simulated ΔSMS, are beyond the limit of what can be reliably quantified using current GRACE satellite products.

Our examination of a large, mass-storage change (2003–2006) observed in the Lake Victoria Basin highlights substantial variability in the measurement of ΔTWS using different gridded GRACE products. Although the phase in ΔTWS is generally well recorded by all tested GRACE products, substantial differences exist in the amplitude of ΔTWS that influence the disaggregation of individual terrestrial stores (e.g. groundwater storage) and the estimation of temporal trends in TWS. Analyses that solely rely upon a single solution disregard the uncertainty in ΔTWS associated with GRACE signal processing. We note, for example, that the stronger filtering of the large-scale (∼ 300 km) gravity signal associated with *GRCTellus* results in greater signal leakage relative to GRGS and JPL-Mascons. As a result, greater rescaling is required to resurrect signal amplitudes in *GRCTellus* relative to GRGS and JPL-Mascons and these scaling factors depend upon uncertain and incomplete a priori knowledge of terrestrial water stores derived from large-scale land-surface or hydrological models, which generally do not consider the existence of Lake Victoria, the second largest lake by area in the world.

Data availability. Descriptive statistics of various GRACE TWS signals and statistical associations with soil moisture derived from GLDAS land-surface models, observed surface water, and groundwater storage changes estimated over the Lake Victoria and Lake Kyoga basins are provided in the Supplement.

The Supplement related to this article is available online at https://doi.org/10.5194/hess-21-4533-2017-supplement.

Author contributions. RT conceived this study for which preliminary analyses were carried out by DJ and MS. MS and DJ have processed GRACE and all observational datasets and conducted statistical analyses and GIS mapping. LL conducted the analysis of spatial leakage and bias in GRACE signals. CT, RT and MO helped to establish, collate and analyse groundwater-level data; CT provided dam release data. MS and RT wrote the manuscript and LL, DJ, MO and CT commented on draft manuscripts.

Competing interests. The authors declare that they have no conflict of interest.

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