Modelling the water balance of Lake Victoria (East Africa), part 1: observational analysis

Hydrology and Earth System Sciences

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Inne Vanderkelen[1], Nicole P. M. van Lipzig[2], Wim Thiery[1, 3]
inne.vanderkelen@vub.be

[1] Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium.
[2] Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E, 3001 Leuven, Belgium.
[3] Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland.

Contents

Abstract

This response letter contains numbered figures and references to these figures. To prevent confusion, the figures embedded within this response letter are called illustrations. Finally, the following convention is applied to denote modification in the original manuscript: new text.

1 Reviewer 1

Reviewer 1 Comment 1

The proposed article describes a water balance model for Lake Victoria, using state-of-the-art remote sensing observations, high resolution reanalysis downscaling and outflow values recorded at the dam. This question had a great significance as the proposed method can be used for other big water objects with scarcity of in-situ observations. Authors underline that it is also possible to force their water balance model with climate simulations for the future to predict the oscillations of water level. The object of research has a major importance as a source of water for local communities, source of food via fishing in addition to transport and energy use. Authors showed that precipitation and dam outflow are the mean causes of seasonal and inter-annual lake level fluctuations. All used data is available online or upon request.

Response

We thank Reviewer 1 for his/her overall support of our study. Below we address the issues that were raised for improvement of the manuscript.

Reviewer 1 Comment 2

According to Atlas "World water balance and water resources of the Earth" (1974), the evaporation from Lake Victoria is estimates as 1500 mm (illustration 1). It confirms that the estimation of evaporation made by the authors is right. It is not clear why the CN model shows that the most runoff is generated in the south west of the Lake Victoria Basin. According to Atlas World water balance and water resources of the Earth (1974) the most runoff is generates in the north west part in the basin (because of the relief peculiarities (illustration 2).

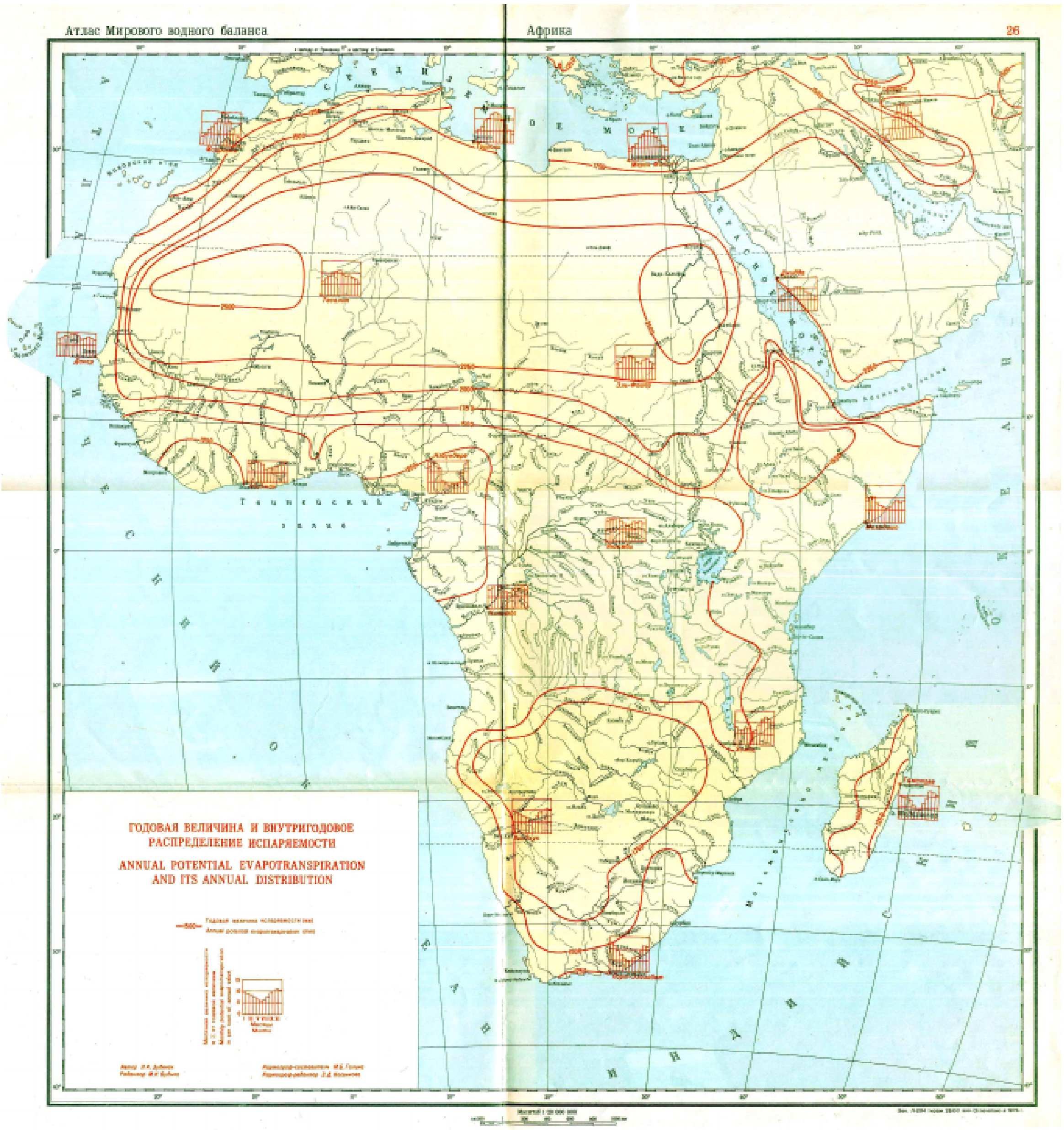

Illustration 1: Evaporation following Atlas "World water balance and water resources of the Earth" (SSSR Gidrometeorologičeskaja et al., 1978).

Illustration 2: Runoff following Atlas "World water balance and water resources of the Earth" (SSSR Gidrometeorologičeskaja et al., 1978).

Response

We thank the reviewer for cross checking our evaporation estimation. We added the extra reference provided by the reviewer in the manuscript.

> The mean annual evaporation over the lake is 1521 mm year^{-1}, which is consistent with the value of 1500 mm year^{-1} reported in SSSR Gidrometeorologičeskaja et al. (1978) and the value of 1595 mm year^{-1} calculated by Piper et al. (1986) and used in the studies of Sene and Plinston (1994) and Tate et al. (2004).

Considering the runoff, in our estimation most runoff is generated in the south east, while following illustration 2 from the Atlas "World water balance and water resources of the Earth" (SSSR Gidrometeorologičeskaja et al., 1978), the highest values can be found in the north east (up to 500 mm year^{-1}). The latter spatial pattern corresponds to the pattern of the annual precipitation as observed in the PERSIANN-CDR precipitation product (illustration 3a).

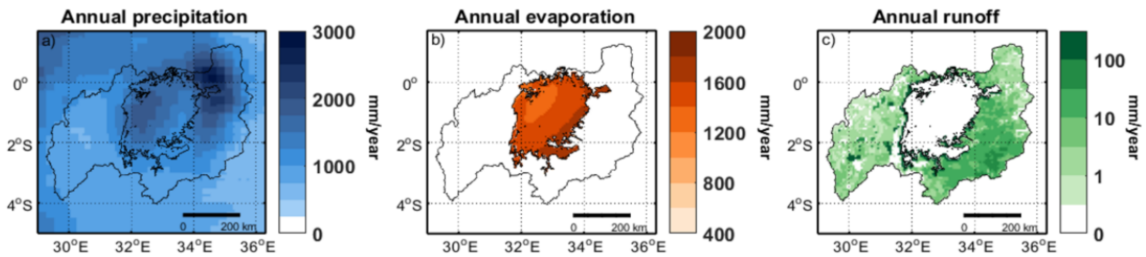

Illustration 3: Climatology form 1993-2014: annual precipitation derived from PERSIANN-CDR observations (a), evaporation from COSMO-CLM^2 model output (b) and runoff calculated with the CN method based on PERSIANN-CDR precipitation observations (c). *Fig. 4 of the paper, added for comparison purpose.*

The difference between the observed precipitation pattern and the calculated runoff pattern can be attributed to the Curve Number (CN) method on which the runoff calculation is based. In the CN method, the runoff is calculated for each pixel in the Lake Victoria Basin based on the precipitation and the Curve Number, which is based on land cover, hydrologic soil class and antecedent moisture condition. To isolate the effect of precipitation on runoff (direct and indirect through the antecedent moisture condition), we calculated the runoff with constant CN values (CN = 70) for each pixel of the basin (illustration 4). As expected, this simulation shows the same spatial distribution as the precipitation (illustration 3a). Consequently, the different spatial pattern of outflow in our study is due to differences in CNs, and thus differences in land cover and hydrologic soil class (illustration 5a and b). For example, in the north eastern part of the basin, the land cover mainly exists of shrubland and a mosaic of forest and cropland. This, in combination with a majority of hydrologic soil class C (moderately high runoff potential), leads to relatively lower CNs (table 1) compared to the south eastern part of the basin, where cropland in combination with hydrologic soil group D (high runoff potential) is abundant (illustration 5).

We added a sentence in the manuscript explaining the different patterns of runoff and precipitation:

> Accordingly, most runoff is generated in the south west of the Lake Victoria Basin (Fig. 5c). The spatial pattern of runoff does not correspond to the pattern of precipitation (Fig. 5a). This is due to the spatial difference in CN numbers (Fig. 6c), which determine the amount of precipitation that results in runoff.

Finally, to get a better view on the variations in CN, we updated the color scale of panel c of figure 6 (illustration 5). In the updated figure the high CNs in the south east are more clearly visible.

Table 1: CN for CN land cover classes and Hydrologic Soil Groups

CN	A	B	C	D
Woods	36	60	73	79
Brush-brush-forbs-grass mixture with brush the major element	35	56	70	77
Pasture, grassland or range-continuous forage for grazing	49	69	79	84
Crops	64	74	81	85
Mosaic forest/cropland	50	67	77	82
Fallow	77	86	91	94
Cities	59	74	82	86
Water bodies	100	100	100	100

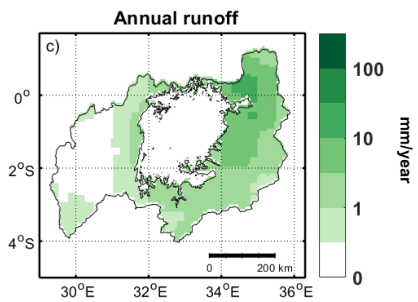

Illustration 4: Annual runoff calculated with a constant CN (70) over the basin.

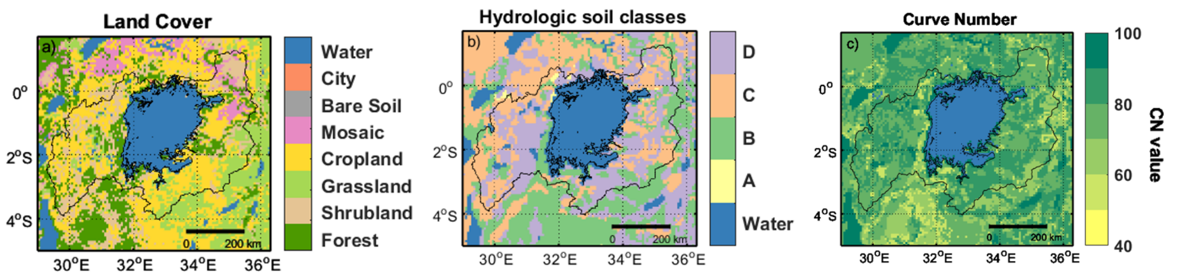

Illustration 5: Updated version of figure 6. The color scale of panel c, showing the CN values, is updated.

Reviewer 1 Comment 3

What is the reason of absence of HYDROMET water level data after 1996?

Response

The HYDROMET in situ lake level data comes from the WMO Hydrological Survey which ended in August 1996, by consequence beyond this date, there are no in situ lake level measurements available from the WMO campaign. We complemented these in situ measurements with the satellite DAHITI dataset. To justify the use of this dataset, we provide here a plot of the water levels from both products in the period for which they are both available (illustration 6). We also added a paragraph in the manuscript describing the used lake level observations (See also Reviewer 2 Comment 9).

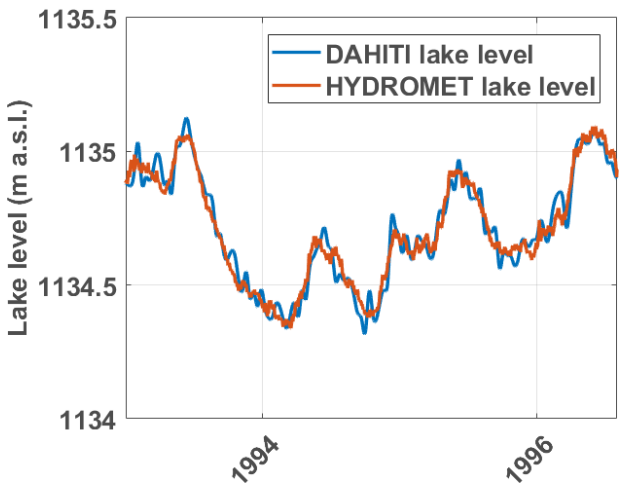

Illustration 6: Zoom on period where both HYDROMET and DAHITI data are available (1st of January 1993 until 1st of August 1996)

Reviewer 1 Comment 4

It is useful to mark points of water level observations and rain gauge stations on the fig. 1.

Response

The water level is measured at the dam, located in Jinja. To clarify this, we updated the caption of figure 1.

> **Figure 1.** Map of Lake Victoria and its basin with surface heights from the Shuttle Radar Topography Mission (SRTM). The outflow amounts and in situ lake levels are measured at Jinja, where the two dams are located.

Since we only use the remote sensing product PERSIANN-CDR, we do not believe it is necessary to mark rain gauge stations on figure 1 . We added a small overview map to help the reader orienting Lake Victoria on a map of Africa.

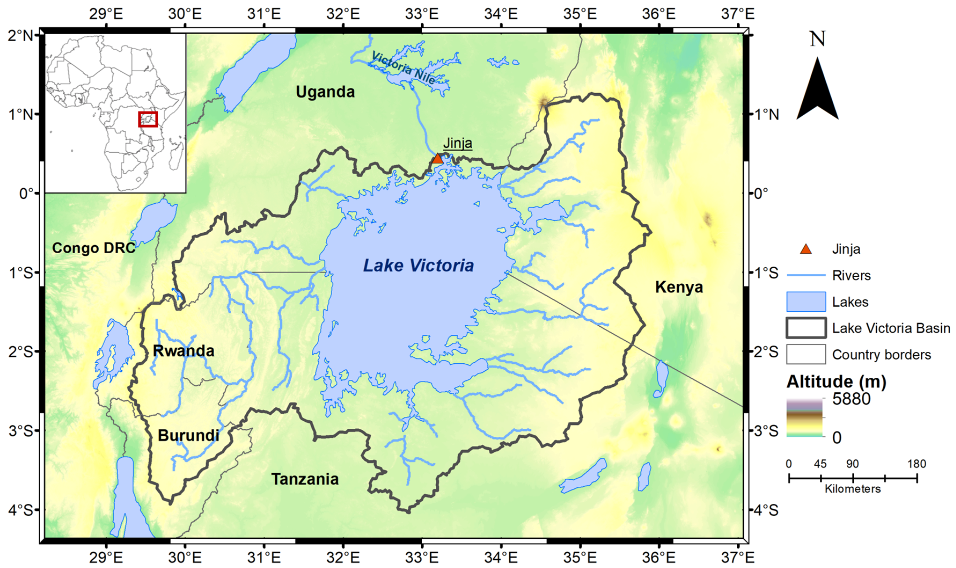

Illustration 7: Updated version of figure 1.

Reviewer 1 Comment 5

On the fig. 5 it is usefull to give all water balance components in the same unit of measure (mm or m3).

Response

Good point, we converted the inflow term in lake level equivalents (mm day^{-1}) and used the same y-axis scales for the three plots in the updated version of figure 5 (illustration 16).

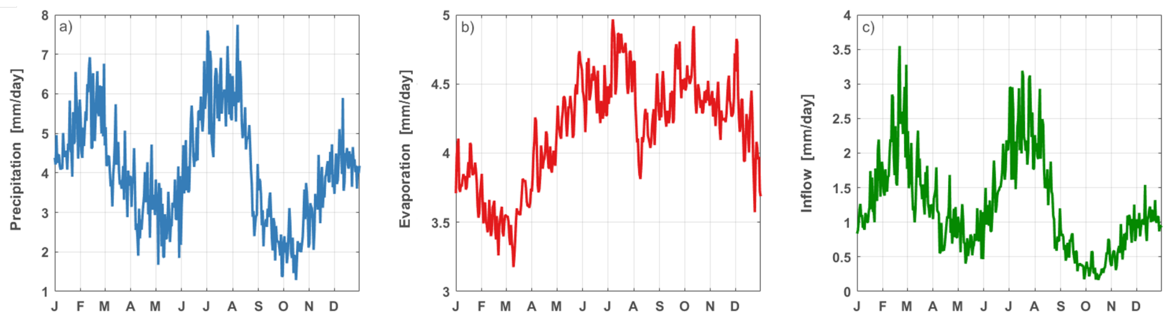

Illustration 8: Updated version of figure 5.

2 Reviewer 2

Reviewer 2 Comment 1

The presentation is clear and quite systematic, the previous studies are discussed and cited accurately. The methods, results and related inaccuracies are presented well and the language is clear. The manuscript could be published with minor modifications. My minor suggestions and some questions are written as comments (done with Adobe Acrobat Reader) to the attached copy of manuscript pdf. It should be possible to copy the remarks to a file in order to reply to them as required.

Response

We thank the Reviewer for the positive comments about the text and structure. Below, we address every comment carefully and explain the corresponding changes in the manuscript.

Reviewer 2 Comment 2

P1, L7: grammatical correction

Response

We thank the reviewer for identifying this grammar mistake and added an -s to the word *yield* in the abstract:

> The uncalibrated computation of the individual water balance terms yields lake level fluctuations that closely match the levels retrieved from satellite altimetry.

Reviewer 2 Comment 3

P3, L4-5: suggestion to make the words *long rains* and *short rains* singular.

Response

We acknowledge the reviewer for reading the text with attention. The terms long rains and short rains (in plural) are however widely used in literature to address the two main rainfall seasons (e.g. Nicholson, 1996; Sene and Plinston, 1994; Tate et al., 2004; Taye et al., 2011; Williams et al., 2015). Therefore we decided to keep the terms as in the original manuscript.

Reviewer 2 Comment 4

P4, L11: Air temperature or lake surface water temperature? What is the role of incoming radiation? Please specify.

Response

We understand the confusion of the reviewer and clarified that it is the near-surface air temperature. We also added a description of the role of incoming radiation in the manuscript.

> Annual evaporation shows little change (Kite, 1981) and is often assumed to be constant in previous water balance model studies (Kite, 1981; Piper et al., 1986; Sene and Plinston, 1994; Tate et al., 2004; Smith and Semazzi, 2014), as water availability is unlimited above a lake surface and near-surface air temperature in the tropics is assumed to be nearly constant. The seasonality of incoming radiation has only a little influence on the latent heat flux and resulting evaporation. Thiery et al. (2014a) showed that above Lake Kivu, located southwest of Lake Victoria, the incoming long-wave radiation and relative humidity experience a drop in the main dry season from June to August due to reduced cloud cover. In addition, due to the drop in relative humidity during the dry season there is a larger potential for evaporation (Thiery et al., 2014a). Monthly variations in downward short-wave radiation have only little effect on evaporation, as it is possible that the monthly variation in top-of-the-atmosphere incoming short-wave radiation is balanced out by monthly varying clouds, leading to more or less constant monthly incoming shortwave radiation at the surface (Thiery et al., 2014a).

The monthly deviation of both net short- and longwave radiation is not more than 10 W m^2, which is a small absolute difference (illustration 9 Thiery et al., 2014a).

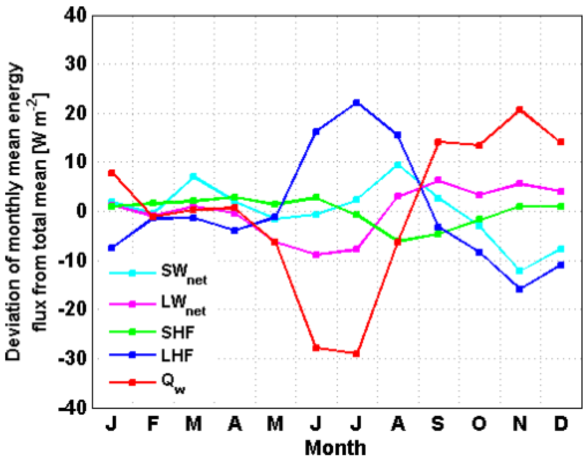

Illustration 9: Deviation from the monthly average of the surface energy balance components from its long-term mean (W m^{-2}) at Ishungu, 2003-2011, calculated by the lake model FLake's surface flux routines. Components of interest are net short-wave radiation (SW_{net}) and net long-wave radiation (LW_{net}) (Adapted from Thiery et al., 2014b).

Reviewer 2 Comment 5

P4, L24: You come back to the comparison numbers in Table 1, subsections 4.1. Please consider systematization of the presentation - perhaps here in section 2 the introductory overview and references, comparison of all results in 4.1.

Response

We agree on a better systematization of the presentation and removed the last sentence of the paragraph at P4 L 23-24. To show the sensitivity and therefore uncertainty of the evaporation estimates in literature, we decided to keep the previous sentence with the ranges of values reported in literature. As the widely used evporation estimation of Piper et al. (1986) lie within this range, these references are added accordingly.

We updated the text as follows:

> However, the calculation of evaporation is very sensitive to assumptions on the meteorological parameters. The various estimations for annual evaporation therefore range from 1350 to 1743 mm/year (Yin and Nicholson, 1998; Piper et al., 1986; Sene and Plinston, 1994; Sutcliffe and Parks, 1999; Tate et al., 2004).

Reviewer 2 Comment 6

P5, L19: Units?

Response

We added the units in the manuscript:

> Since then, the outflow is regulated by the Agreed Curve, a rating curve relating lake level and outflow in natural conditions. This relation is quantified by Sene (2000) as:
>
> $$Q_{out} = 66.3(L - 7.96)^{2.01} \quad (1)$$
>
> with Q_{out} (m^3 day^{-1}), the outflow and L (m day^{-1}), the lake level.

Reviewer 2 Comment 7

P6, L14: For a further study, if not here; would it be possible to compare the COSMO reanalysis precipitation data to these observations? In any case you use reanalysis for derivation of the evaporation. Most probably, evaporation and precipitation in the reanalysis are consistent as they are processed with the same NWP model. Usage of climate model precipitation data for the future might be motivated or their uncertainties discussed from this perspective.

Response

The COSMO-CLM^2 reanalysis downscaling of precipitation has been compared to various observational data sets (illustration 10; Thiery et al., 2015). This comparison pointed out that the observed precipitation patterns are reasonably reproduced by COSMO-CLM^2 (see CTL, illustration 10d). In detail, COSMO-CLM^2 is able to represent the enhanced precipitation over the surface of Lake Victoria as recorded by the TRMM products, but underestimates the amount of annual precipitation compared to both TRMM products (-24% dry bias relative to TRMM 3B42 and -30% relative to TRMM 2B31; Thiery et al., 2015). In contrast, compared to the GPCP and CMORPH products, COSMO-CLM^2 overestimates the precipitation respectively by 16% and 19% (Thiery et al., 2015). The maximum difference between the observational products is however larger than the biases between COSMO-CLM^2 and the individual products (illustration 10h Thiery et al., 2015). PERSIANN-CDR, the precipitation product used in this study (illustration 11), is not included in the evaluation of Thiery et al.

(2015). Nevertheless, a rough comparison learns that relative to PERSIANN-CDR, the precipitation amounts according to COSMO-CLM^2 do not underestimate the precipitation over Lake Victoria. The spatial pattern of the enhanced precipitation following COSMO-CLM^2 is however shifted towards the north east, while the enhanced precipitation is centered on the western half of the lake for PERSIANN-CDR and also both TRMM, GPCP and CMORPH data products.

In the second part of this two part paper series, we evaluated reanalysis precipitation and evaporation of regional climate models from the Coordinated Regional Downscaling Experiment (CORDEX) over the Africa domain to motivate the use of future simulations. We found that generally, regional climate models running at 50km resolution are not capable of providing reliable representations of the climate in the Lake Victoria region. For a detailed description we refer to Vanderkelen et al. (2018).

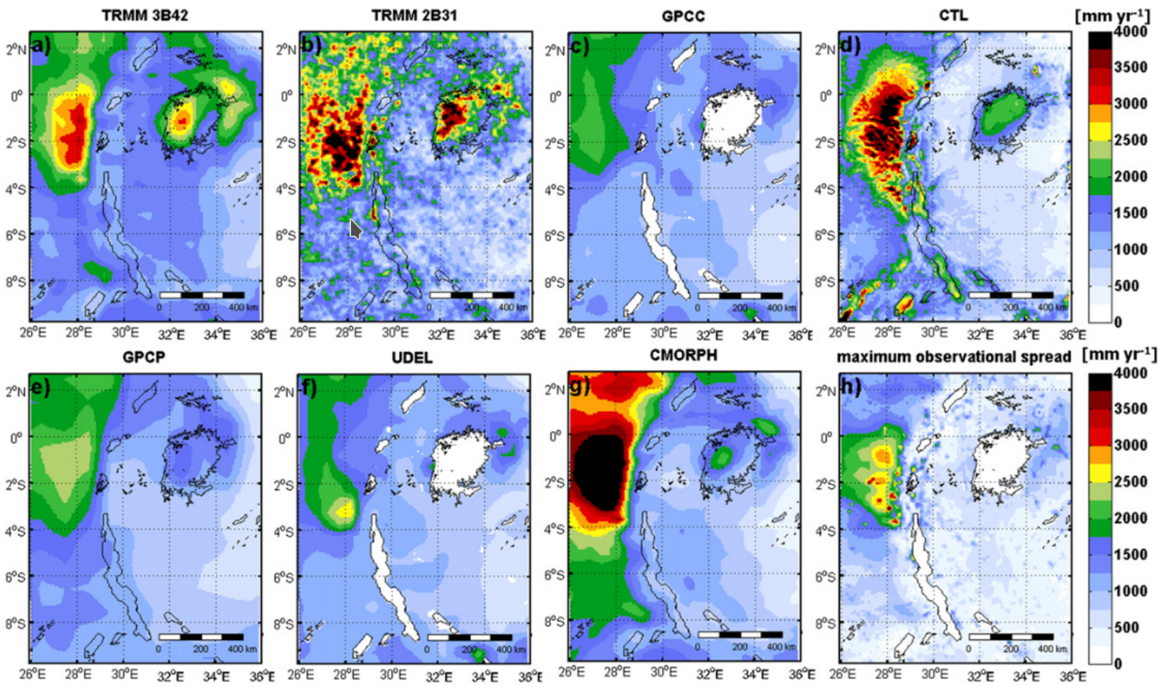

Illustration 10: Observed annual mean precipitation P (mm year^{1}) (a) TRMM 3B42, (b) TRMM 2B31, (c) GPCC, (e) GPCP, (f) UDEL, and (g), CMORPH - averaged over the period 1999-2008 (CMOPRH data is averaged over 2003-2008). (d) the 1999-2008 modelled P with COSMO-CLM^2, (h) maximum difference among obervational products considering only land pixels. The observational products GPCC and UDEL are masked out over the lakes as they are based solely on land station data. (Adapted from Thiery et al., 2015).

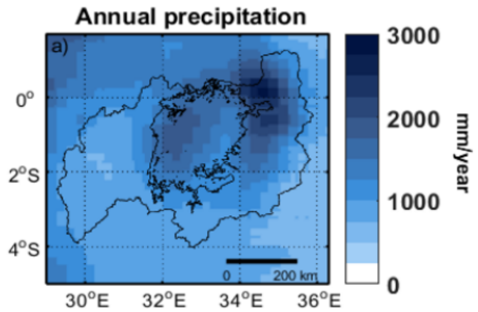

Illustration 11: Annual precipitation derived from PERSIANN-CDR, climatology from 1993-2014 (figure 4 panel a).

Reviewer 2 Comment 8

P6, L18: Probably yes, but at line 1-2 this page you address the smallest relative uncertainty just to the evaporation?

Response

We clarified this point by distinguishing the two uncertainties, as the uncertainty estimates addressed at line 1-2 are our own calculations based on the estimates of water balance terms reported in literature, whereas the statement that evaporation estimates are denoted as one of the largest sources of uncertainty, was found in the literature itself and was formulated based on the uncertainty induced by the calculation methods of evaporation. The apparent discrepancy is due to the fact that our calculated ranges do not correspond to the notions of uncertainty reported in literature.

We updated the manuscript as follows (line 18-19):

> Yin and Nicholson (1998) and Swenson and Wahr (2009) denoted evaporation estimates as the one of the largest sources of uncertainty of Lake Victoria's water balance based on uncertainties related to the calculation method for evaporation due to the lack of in situ observations. However, in our uncertainty estimations using all reported values for the three WB terms, lake evaporation estimations have the smallest range.

Reviewer 2 Comment 9

P7, L19: You might mention the pixel size already here.

Response

We added the pixel size on P7, L18:

> Here, the CN method is applied on pixel level: each pixel (about 7 by 7 km) is assigned a CN value, after which the resulting pixel runoff is calculated based on the pixel precipitation.

Reviewer 2 Comment 10

P8, L02: Are there other possibilities to characterize soil properties, soil moisture etc? SOILGRIDS http://isric.org/explore/soilgrids? Soil moisture from remote sensing?

Response

We considered other possibilities to characterize soil properties. However, the CN method is constructed in such a way that soil moisture is not taken into account directly. Theoretically, it would be possible to retrieve the antecedent moisture condition from the amount of soil moisture. At the moment, the antecedent moisture condition is only calculated based on precipitation of the last 5 days. To use soil moisture for determining the antecedent moisture condition, the CN method itself would need to be recalibrated.

The Soil Grid dataset provided by ISRIC uses global spatial prediction models based on a compilation of major international soil profile databases and a selection of global environmental covariates representing soil forming factors (Hengl et al., 2017, 2014). This dataset provides different layers with physical soil properties such as clay content, coarse fragments, silt content and sand content, which could be used to determine the hydrologic soil class. During the WBM construction, we were not aware of the existence of this high resolution dataset. If we would use this dataset, a set of rules would have to be developed to classify the variables provided by SOILGRIDS (e.g. % clay content on different depths) to hydrologic soil groups as described in table A3. This reclassification is however not trivial. A lot of effort was already put into the reclassification of World Reference Based soil into hydrologic soil groups. Therefore, we included a part at the end of the discussion (P17 L14) to describe avenues for future research to investigate the sensitivity of the observational WBM to different input datasets, like SOILGRIDS.

> Future research could focus on the sensitivity of the observational WBM, by feeding the model with other input datasets, e.g. SOILGRIDS (Hengl et al., 2014, 2017) to determine the hydrologic soil group, Tropical Rainfall Measuring Mission (TRMM) products (Kummerow et al., 2000) and products from the Global Precipitation Climatology Project (GPCP; Huffman et al., 2001) and runoff datasets like the Global Streamflow Indices and Metadata Archive (GSIM; Do et al., 2017; Gudmundsson et al., 2017) and data provided by the Global Runoff Data Centre (GRDC).

Reviewer 2 Comment 11

P8, L25: Compared to all other sections, this is the most detailed. Would it be perhaps possible to condense it, using references to things that were not invented in this study or moving some text on the details to the appendixes where the tables already are? On the other hand, discussion of the connection between the precipitation data and inflow which are tied together with this methods, might be interesting to the reader.

Response

We agree that this paragraph is longer than the other paragraphs in the data and methods section. Therefore we condensed it by moving the detailed explanation of the land use classification, hydrological soil classes and antecedent moisture condition to the appendix section. However, we agree with the reviewer that the relation between precipitation and inflow through the CN is important information for the reader, so we kept the two equations showing this relation in the manuscript.

We updated the text as following:

> Inflow by tributary rivers is calculated using the Soil Conservation Service-Curve Number method (hereafter denoted as the CN method; NEH4, 2004b). This method relates daily precipitation (P) to daily runoff (R) through the Curve Number (CN), obtained based on an empirical model, with parameters associated to land use, hydrological soil types and antecedent hydrological conditions. It has been shown that simple runoff models like the CN method with a few input parameters can provide results that are at least as good as more complex rainfall-runoff models (Van den Putte et al., 2013). Here, the CN method is applied on pixel level: each pixel (about 7 by 7 km) is assigned a CN value based on the land cover and soil type of the pixel, after which the resulting pixel runoff is calculated based on the pixel precipitation. Land cover classes are derived from the Global Land Cover 2000 project (GLC 2000; Mayaux et al., 2003, following Maetens (2013); see appendix for more details). For each pixel, a hydrological soil class is determined based on soil data from the Soil Atlas of Africa (see appendix; Dewitte et al., 2013). Thirdly, the CN number is dependent on the hydrological condition, which is taken into account by the Antecedent Moisture Condition (AMC) based on the cumulative precipitation over the 5 past days (see appendix). By implementing the AMC, the CN becomes time dependent. In the next step, the CN is used to calculate the maximum soil water retention parameter (S, equation 2) (NEH4, 2004a). Finally, the runoff R_d (m^3 day^{-1}) is calculated based on the daily precipitation P_d (m day^{-1}) and maximum soil water retention parameter (S) (equation 3).

$$S = \frac{25400}{CN - 254} \tag{2}$$

$$\begin{cases} R_d = 0 \quad if \quad P_d > 0.2S \\ R_d = \frac{(P_d - 0.2S)^2}{P_d + 0.8S} \quad if \quad P_d \le 0.2S \end{cases} \tag{3}$$

> Total daily inflow is obtained by summing the calculated runoff of all basin pixels. As the pixels are large sized (about 7 by 7 km), it can be assumed that pixel runoff leaves the pixel by flowing in water channels. This assumption makes that runoff routing over the basin pixels is not necessary, as is the case with smaller pixel sizes (e.g. for pixels of 200 by 200 m; Moglen, 2001).

We added the details about the land cover, hydrological soil class and equations to transform the CN according to the antecedent moisture condition to the appendix section.

> **Appendix A: Curve Number calculation** The CN number is calculated based on the land cover, hydrological soil class and antecedent moisture condition. This section gives the detailed methodology for determining the CN number of each pixel in the study area. The original GLC 2000 land cover classes are grouped

and reclassified in more general classes (see table A1). Each of these general classes is subsequently coupled to a corresponding land cover class with known CNs (see table A2). This coupling is based on the classification of Maetens (2013) who reclassified similar land cover classes into CN classes. The hydrological soil groups (table A3) are defined based on soil data from the Soil Atlas of Africa (Dewitte et al., 2013), classified according to the World Reference Base soil classification and converted to hydrological soil group based on table A4. Using table A5 based on the land cover and hydrological soil group, the CNs are determined for all pixels in the lake basin. Next to land cover and soil type, the CN is also dependent on the hydrological condition of a certain pixel. This is taken into account by the Antecedent Moisture Condition (AMC), ranging from AMC I (dry) to AMC III (wet) (Ponce and Hawkins, 1996). The AMC of a certain pixel is determined based on the cumulative precipitation of the 5 past days, as defined in table A6 (Descheemaeker et al., 2008). In case of dry or wet conditions (AMC I and III), the CN is converted using equations 4 and 5, where CN_{II} presents the first (default) calculated CN (Ponce and Hawkins, 1996).

$$CN_I = \frac{CN_{II}}{0.427 + 0.00573 CN_{II}} \tag{4}$$

$$CN_{III} = \frac{CN_{II}}{2.281 - 0.01281 CN_{II}} \tag{5}$$

Reviewer 2 Comment 12

P8, L25: Also, would the (simplified) runoff given by reanalysis or hydrological models of any use for your study? Would it be possible to compare different alternatives?

Response

We thank the reviewer for raising this point. A comparison with a gridded, observation-based runoff dataset would indeed increase the quality of the paper. To date, there is however no gridded dataset of observed runoff available for East-Africa. Gudmundsson and Seneviratne (2015) developed a framework to estimate continental-scale runoff in Europe on a 0.5°spatial grid with monthly resolution based on observed streamflow of small catchments. This data product is however only available for Europe.

A first alternative would be to use in situ runoff observations. This is however unconventional due to scarcity of observations and spatial inconsistencies between catchment and pixel area. In the past, inflow in Lake Victoria has been measured in an hydrological survey initiated by WMO. These measurements encompass however a lot of gaps and are not available for the considered period (1993-2014). In recent years, satellite remote sensing as measurement tool for total water storage emerged (specific for Lake Victoria, e.g. Swenson and Wahr, 2009; Hassan and Jin, 2014). These satellite observations cover a limited timeframe and encompass still uncertainties due to retrieval algorithms (Landerer and Swenson, 2012).

A third alternative is to compare the calculated runoff to land surface models and hydrological models driven by historical or reanalysis forcing (e.g. Fekete et al., 2002; Balsamo et al., 2015). Although these products provide spatial and temporal comprehensive data, the model results encompass large uncertainties and are still highly model dependent (Haddeland et al., 2012; Gudmundsson et al., 2012; Prudhomme et al., 2014).

Although important shortcomings persist in current available runoff products, it could be part of future research to test the sensitivity of our model to using various input data sources.

Reviewer 2 Comment 13

P9, L19: Perhaps here a short paragraph: *3.6. Data and methods for validation*
Now it seems that this is only mentioned in the caption for Fig.2, while a systematic presentation with references is needed.

Response

We agree with Reviewer 2 and added an extra paragraph explaining the lake level observations against which the modelled lake levels are compared.

> **3.6 Evaluation data**
> The performance of the WBM is assessed by comparing the modelled water levels to observed water levels. Observed Lake Victoria water levels are retrieved from the open-acces Database for Hydrological Time Series of Inland Waters (DAHITI) (Schwatke et al., 2015). The water level time series are derived from multi-mission satellite altimetry and were processed using an extended outlier detection algorithm and a Kalman filter (Schwatke et al., 2015). Lake Victoria water levels are measured about three times per month from September 1992 until present day in absolute heights with reference to the EIGEN-6c3stat geoid model (Schwatke et al., 2015). In addition, in situ lake level measurements from the WMO Hydrometeorological Survey are used (WMO, 1981; Kite, 1981). This data gives the measured lake depth at Jinja, but can be converted to meters above sea level using the associated datum. The daily lake level series covers the period 1/1/1948 until 1/8/1996, with data gaps in the years 1977, 1978, 1979, 1981 and 1982. These data gaps are filled with linear interpolation. Both lake level datasets are plotted in figure 12 for the period 1950-2014. The lake levels overlap from September 1992 to August 1996. During this period they closely match, which justifies the use of both products together.

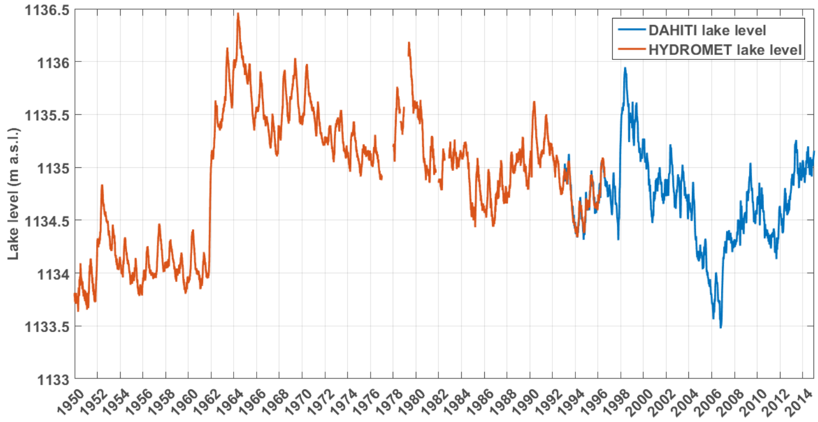

Illustration 12: Lake Victoria historical water levels: HYDROMET: in situ measurements from the World Meteorological Organisation (WMO) Hydrometrological survey from 1950 to 1996 with data gaps in 1977, 1978, 1979, 1981 and 1982 (WMO, 1981), converted from measured lake depth at Jinja, to meters above sea level using the EIGEN-6c3stat geoid model. DAHITI satellite altimetry measurements from 1992 to 2014 (Schwatke et al., 2015).

Reviewer 2 Comment 14

P10, figure 5: Not the scale only, the unit of the variables is different.

Response

We converted the units of inflow to mm day^{-1} and updated the figure (illustration 16; see Reviewer 1 Comment 4).

Reviewer 2 Comment 15

P11, L09: Which temperature? Dependency of relative humidity on air temperature may influence the result?

Response

In the revised manuscript, we now specify that this deals with the near-surface air temperature in the text. The mean annual cycle of near surface air temperature over the African Great Lakes ranges between 295 and 299 K, with a difference of 4 K (see illustration 13; Thiery et al., 2015). Moreover, the annual evaporation (illustration 14) with the observed temperature (illustration 15; Thiery et al., 2015), do not correspond, which strengthens our statement.

We updated this in the manuscript:

> This spatial pattern does not follow the pattern of observed lake temperature (Thiery et al., 2015), which is consistent with the idea that the spatial pattern of evaporation is primarily driven by the relative humidity rather than by near-surface air temperature (Thiery et al., 2014a,b). Moreover, the spatial pattern of

evaporation could be explained by the advection of dry winds from the south (the Serengeti area). While blowing in a northwest direction over the lake, these winds take up more moisture. Likewise, their evaporation potential decreases.

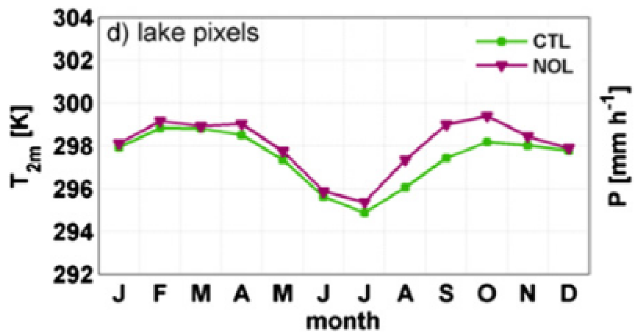

Illustration 13: Averaged seasonal cycle of T_{2m} of the lakes in the African Great Lake region over the period 1999-2008. *(Adapted from Thiery et al., 2015)*

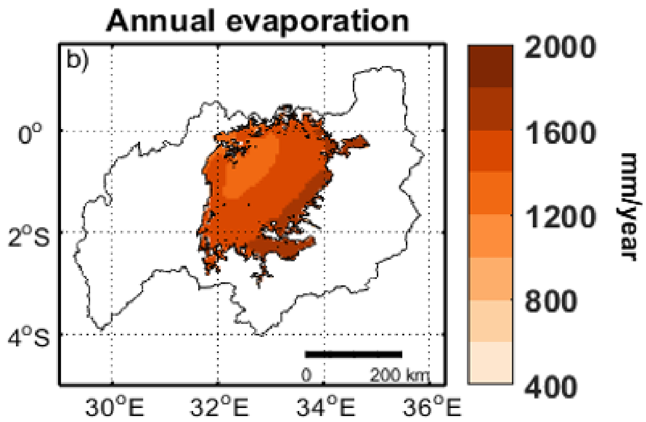

Illustration 14: Annual evaporation as in figure 4b

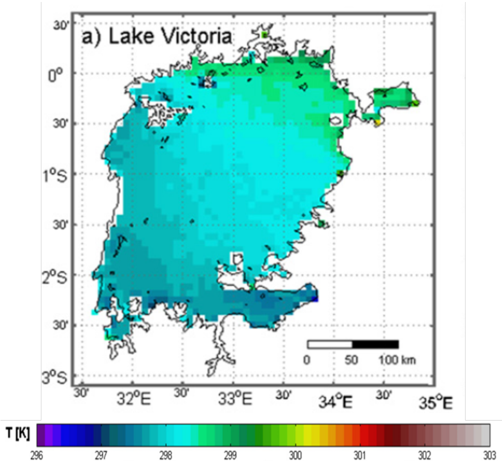

Illustration 15: Observed temperature of Lake Victoria *(Adapted from Thiery et al., 2015)*

Reviewer 2 Comment 16

P10, figure 7: Would it be possible to plot also the (small) residual in this Figure?

Response

We agree with the comment of the reviewer and added the annual cycle of the residual to figure 7 (see illustration 16). In the annual cycle, the residual follows a similar course as the lake precipitation, representing the two rainy seasons (illustration 16). As expected, the annual cycle of the residual is consistent with the seasonal cycle of the lake levels (figure 10), with rising lake levels during the two rainy seasons, the long rains during March, April and May and the short rains during September, October and November. The cumulative residual for the whole observational period, which is the result of combining all water balance terms, is already shown in figure 8 as the lake level.

We added the description of the annual cycle of residual in the manuscript in the paragraph discussing this figure:

> The outflow however does change up to 266 % on inter-annual time scales (Fig. 3). The annual cycle of the WB residual reflects bimodal variation of the precipitation and inflow term with positive values during the two rainy seasons (Fig. 7). The residual knows a large variation on monthly time scales, similar to the variation in precipitation. On annual time scales, the residual is however rather small, with an annual mean residual of 0.23 m year^{-1}.

And in the paragraph discussing the seasonal cycle of the modelled and observed lake levels:

> A similar correspondence is found in the seasonal cycle of the lake level (Fig. 10), with on average the highest accumulation rates observed around the end of May and the beginning of June and the highest water loss around end of Septem-

ber and October. This behaviour is consistent with the seasonal cycle of the WB residual (Fig. 7): the lake level rises during the two rainy seasons (positive residual) and falls again during the dry seasons (negative residual). Likewise, as the annual variation of the WB residual is primarily driven by precipitation, its seasonality provides each year two seasonal recharges. The difference between the two accumulation peaks, the first around the end of January and the second around the end of May, can be attributed to the larger decrease during the main dry season in June, July and August than during the other dry season in February.

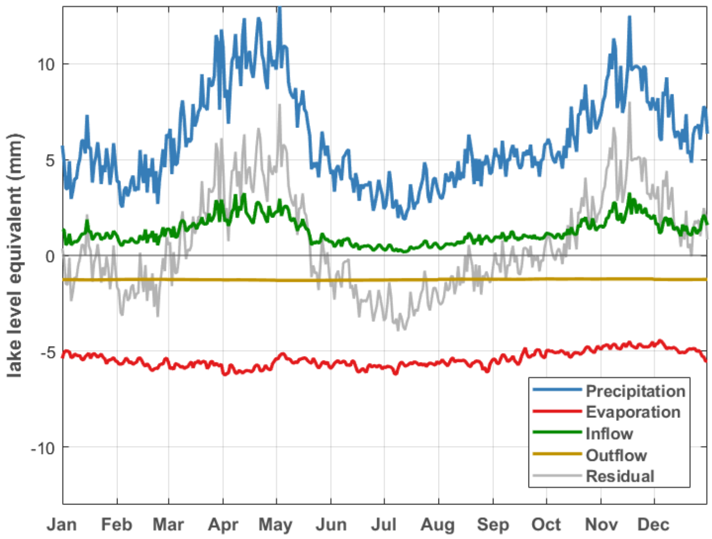

Illustration 16: Seasonal cycle of the water balance terms and residual for the period 1993-2014.

Reviewer 2 Comment 17

P10, figure 8: This Figure shows the relations between the terms of balance and the lake level well, but perhaps it would be good to show the level using another scale, e.g. from -4 to 4 instead of the bulk -40 to 40?

Response

The relative lake level or lake level anomaly as shown in figure 8, has the same course as the modelled lake level in absolute height showed in figure 9. The difference between those two graphs is the initial value of the lake level in 1993 (1134.9 m). To illustrate this, we added a zoom on the lake level anomalies of figure 7 (illustration 17). We decided to not include this figure in the paper, as it provides no added value compared to figure 9. We added a short sentence in the text (P 13 L 3-4) to clarify the relation between figure 7 and 8:

> The difference of the input and output terms results in lake level variations around the zero line. By adding the initial lake level, the variations in the absolute lake

levels are reflected (Fig. 9).

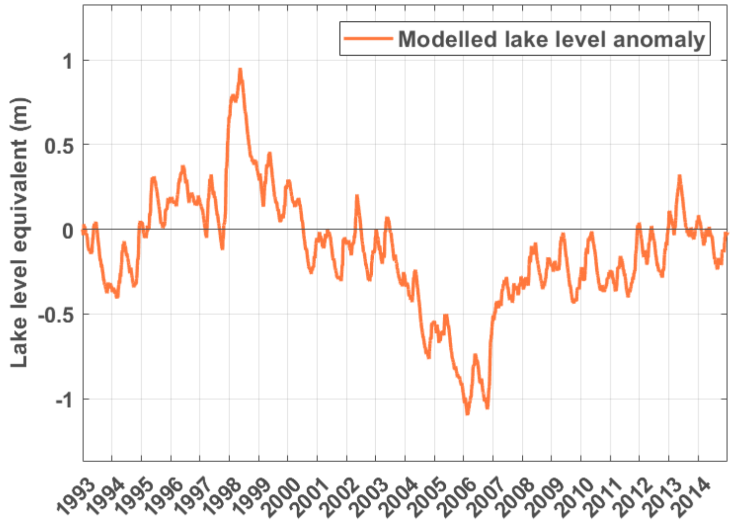

Illustration 17: Modelled lake level anomaly

Reviewer 2 Comment 18

P16, L20: Please show the residual in some of the figures, e.g. Figure 7?

Response

A residual is now included in Figure 7, see our response to comment 16.

Reviewer 2 Comment 19

P17, L12: The title of this manuscript is "Modelling the water balance .... Part 1" What is the plan for part 2? Could be mentioned in the introduction or here.

Response In the second part of this two-paper series, we made future projections for the water level of Lake Victoria. We added references to the second paper in

(i) the abstract (P1, L5):

> In his first part of a two-paper series, we present a water balance model for Lake Victoria, using state-of-the-art remote sensing observations, high resolution reanalysis downscaling and outflow values recorded at the dam.

(ii) the introduction (P2, L16):

> In his first part of a two-paper series, we build an observational Water Balance Model (WBM) to reconstruct the observed Lake Victoria water levels from in situ and high-quality satellite observations and a high-resolution reanalysis downscaling

(iii) and conclusion (P17, L7-12):

> A major advantage of this approach is that it is now possible to force the WBM with climate simulations for the future, which show a decrease in annual precipitation amounts over Lake Victoria (Souverijns et al., 2016). In the second part of this two-paper series, future projections of the evolution of Lake Victoria's lake level are made for the first time (Vanderkelen et al., 2018). These projections are especially relevant given the high societal importance of the future behaviour of the water levels. Changes in the water levels can have far reaching consequences for the people living in the basin, water availability downstream in the Nile Basin and for estimating the future potential for hydropower generation.

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