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# Satellite-based estimates of surface water dynamics in the Congo River Basin

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## Abstract

In the Congo River Basin (CRB), due to the lack of contemporary in situ observations, there is a limited understanding of the large-scale variability of its present-day hydrologic components and their link with climate. In this context, remote sensing observations provide a unique opportunity to better characterize those dynamics. Analyzing the Global Inundation Extent Multi-Satellite (GIEMS) time series, we first show that surface water extent (SWE) exhibits marked seasonal patterns, well distributed along the major rivers and their tributaries, and with two annual maxima located: i) in the lakes region of the Lwalaba sub-basin and ii) in the “Cuvette Centrale”, including Tumba and Mai-Ndombe Lakes. At an interannual time scale, we show that SWE variability is influenced by ENSO and the Indian Ocean dipole events. We then estimate water level maps and surface water storage (SWS) in floodplains, lakes, rivers and wetlands of the CRB, over the period 2003-2007, using a multi-satellite approach, which combines the GIEMS dataset with the water level measurements derived from the ENVISAT altimeter heights. The mean annual

variation in SWS in the CRB is  $81 \pm 24 \text{ km}^3$  and contributes to  $19 \pm 5 \%$  of the annual variations of GRACE-derived terrestrial water storage ( $33 \pm 7 \%$  in the Middle Congo). It represents also  $\sim 6 \pm 2 \%$  of the annual water volume that flows from the Congo River into the Atlantic Ocean.

**Keywords:** Surface water storage; Congo River Basin; Remote sensing.

## 1. Introduction

Despite its importance, the Congo River Basin (CRB), located in the central region of Africa, has not attracted as much attention among the climate and hydrology communities as has the Amazon Basin or other large rivers in the world [Alsdorf *et al.*, 2016]. Up to now, there is still an insufficient knowledge of the regional hydro-climatic characteristics and changes in this region, even though the CRB plays a crucial role at global and regional scales. Firstly, the CRB is remarkable as the second largest river system of the world in terms of both water discharge, with a mean annual flow of  $\sim 40,600 \text{ m}^3/\text{s}$ , and drainage basin size ( $\sim 3.7 \times 10^6 \text{ km}^2$ ) [Laraque *et al.*, 2001, 2009]. It also plays a key role in the Earth system as one of the three main convective centers in the Tropics, with the Amazon River basin and the ‘maritime continent’ of Eastern Indian and western tropical Pacific Oceans [Hastenrath, 1985]. Secondly, more than 80% of people in the CRB live exclusively on activities that are highly dependent on climate and water resource availability: fisheries, agriculture and livestock [Bele *et al.*, 2010]. In this region, the food production depends heavily on rain-fed agriculture, leading the population particularly vulnerable to food insecurity [Brown *et al.*, 2014]. Moreover, a couple of studies have shown that the CRB has already experienced changes in climate variability and in the hydrological system [Mahé and Olivry, 1999; Camberlin *et al.*, 2001; Laraque *et al.*, 2001; Samba *et al.*, 2008; Samba and Nganga, 2012]. Thirdly, about 50% of the CRB land area is covered by tropical forest ( $\sim 190 \times 10^6 \text{ ha}$ , Verhegghen *et al.*, 2012), representing about

18% of the world's tropical forests ( $\sim 1100 \cdot 10^6$  ha, *Achard et al.*, 2002), and playing a crucial role as a sink of CO<sub>2</sub>, storing about 50 billion tons of carbon [*Verhegghen et al.*, 2012]. In a recent study, *Dargie et al.*, [2017] highlighted that the “Cuvette Centrale” peatland (Fig.1) stores about 30 billion tons of carbon. This total amount of carbon is equivalent to  $\sim 80$  billion tons of CO<sub>2</sub> or about 2.3 years of current global anthropogenic emissions ( $\sim 35$  billion tons in 2015, *Olivier et al.*, 2016). This stock is particularly vulnerable to land-use change and any future change in the water cycle. For all these reasons, there is an obvious need to better understand the CRB dynamic and to characterize its vulnerability to climate change and other crucial challenges. In particular, it is necessary to gain solid knowledge about the past and current hydro-climate processes of the CRB, in order to significantly reduce the uncertainties associated with future climate response under global warming. The limited understanding of the CRB's hydro-climate processes results mainly from the lack of *in situ* data availability: the network of stations, which data are publicly released, is sparse and poorly maintained, and it is substantially difficult of perform fieldwork, notably in the swamps. However, recent developments and improvements in remote sensing technology provide more observations than ever before [*Alsdorf et al.*, 2007; *Prigent et al.*, 2016] and allow us the unique opportunity to better understand the spatial and temporal variability of the CRB's hydro-climatic patterns.

In this study, our primary focus is on the CRB surface water (SW) dynamics, a key component of the land water budget equation. The SW, corresponding to water stored in rivers, lakes, wetlands, floodplains and in man-made reservoirs, is crucial to the survival of all living organisms, including humans and is a precious resource in term of biodiversity, ecology, water management and economy. Moreover, SW storage (SWS) plays a major role at all scales in the terrestrial water balance and in the Earth's climate system variability, through its interactions with the atmosphere and ocean. Up until now, the

81 spatial and temporal dynamics of SW stored on the Earth's surface remains still largely  
82 unknown [Alsdorf *et al.*, 2007]. Since the last decades, progresses in satellite remote  
83 sensing are improving substantially our understanding of SW dynamics in the major river  
84 basins of the world. Among these derived-products, radar altimetry is providing since the  
85 early 1990s a monitoring of water levels variations of lakes, rivers, floodplains and  
86 reservoirs [Birkett, 1995; Crétaux and Birkett, 2006; Calmant *et al.*, 2008]. Additionally, it  
87 is possible to extract locally the extent of water bodies using satellite imagery, which,  
88 combined with altimetry data, enable the SWS estimation of lakes and reservoirs [Baup *et*  
89 *al.*, 2014; Crétaux *et al.*, 2016] and of floodplains [Frappart *et al.*, 2005]. More recently,  
90 merging information derived from active and passive microwave sensors and from optical  
91 data, the Global Inundation Extent from Multi-Satellite (GIEMS) dataset [Prigent *et al.*,  
92 2007; Papa *et al.*, 2010; Prigent *et al.*, 2016] offers unprecedented information on the  
93 variations of SW extent (SWE) at the global scale. The combination of GIEMS estimates  
94 with radar altimetry observations has further allowed the provision of spatio-temporal  
95 variations of SWS in large tropical river basins, such as the Amazon, Ganges–Brahmaputra  
96 and Orinoco basins [Frappart *et al.*, 2008, 2010, 2012, 2015b; Papa *et al.*, 2015].  
97 Recently, a few studies tried to understand the SW dynamics in the CRB using remote  
98 sensing and/or modeling [Rosenqvist and Birkett, 2002; Bwangoy *et al.*, 2010; Jung *et al.*,  
99 2010; Beighley *et al.*, 2011; Lee *et al.*, 2011; Tshimanga *et al.*, 2011; Tshimanga and  
100 Hughes, 2012; O'Loughlin *et al.*, 2013; Becker *et al.*, 2014; Betbeder *et al.*, 2014; Lee *et*  
101 *al.*, 2014, 2015]. For instance, Rosenqvist and Birkett, [2002] demonstrated that Synthetic  
102 Aperture Radar (SAR) image mosaics can be used to appraise the maximum extents of  
103 flooding in the CRB, but were not relevant to assess the SW dynamics and ranges of the  
104 variations. Bwangoy *et al.*, [2010] demonstrated the utility of optical and radar remotely  
105 sensed data in characterizing the wetlands of the “Cuvette Centrale”. They estimated that  
106 the wetlands cover an area of 32% in the “Cuvette Centrale”, equivalent to 360000 km<sup>2</sup>.

*Crowley et al.*, [2006], using Gravity Recovery and Climate Experiment (GRACE) data, estimated the terrestrial water storage (surface water storage plus groundwater storage and soil moisture) within the CRB. Over 4 years (2002-2006), the estimate exhibited significant seasonal variations ( $30 \pm 6$  mm of equivalent water thickness) and long-term negative trend ( $\sim -70 \text{ km}^3/\text{year}$ ). *Lee et al.*, [2011], using GRACE data and other satellite measurements, estimated that the amount of water annually filling and draining the Congo wetlands is about  $111 \text{ km}^3$ , i.e. one-third the magnitude of the water volumes found on the mainstream Amazon floodplain. *Lee et al.*, [2014], integrating terrestrial water storage (TWS) changes from GRACE, water level changes from radar altimetry, and inundation extents from SAR imagery, quantified TWS change and its surface and subsurface components over the central CRB. They showed that annual variations of the TWS changes during the period of 2007–2010 from  $21$  to  $31 \text{ km}^3$  and are mostly controlled by surface storage changes. *Lee et al.*, [2015] developed water depth maps over the “Cuvette Centrale” based on a linear regression model from altimetry and imagery data. They reported in their study area water storage volumes of about  $11 \text{ km}^3$  (Dec-2006),  $10 \text{ km}^3$  (Dec-2007), and  $9 \text{ km}^3$  (Dec-2008). Finally, *Becker et al.*, [2014] released an unprecedented dataset of water level time series over the entire CRB for the period 2003 to 2009, obtained from the ENVISAT radar altimetry mission. From this unique data set, they proposed an altimeter-based river level height regionalization scheme and thus identified nine distinct hydrological regions in the CRB.

Hence, to supplement this work, we analyze the spatio-temporal variability of SW extent and storage in the CRB, at seasonal and interannual time-scales. For this, along with GIEMS data covering the period 1993-2007, we further develop the observation-based technique combining SWE and radar altimetry measurements [*Frappart et al.*, 2008] to estimate the CRB’s SWS variations over the period 2003–2007. The results are evaluated

and analyzed along with other *in situ* and remote sensing measurements of three hydrological parameters (discharge, rainfall and terrestrial water storage). The comparisons with the latter will provide, for the first time, the time series of both SW and sub-surface water (SSW) variations distributed throughout the CRB. The paper is structured as follows. In Section 2 we briefly describe the CRB. Section 3 presents the datasets used in this study. In Section 4, we analyze the SWE dynamics from the GIEMS dataset at both seasonal and interannual time-scales for the period 1993 to 2007. Section 5 describes the methodology for deriving SWS from a combination of multi-satellite observations and the results are presented and discussed over the 2003–2007 period. Finally, conclusions and perspectives are presented in Section 6.

## **2. The study region: The Congo River Basin (CRB)**

The CRB is a transboundary basin located in equatorial Africa (Fig. 1). In the heart of the CRB, the shallow depression along the equator is named the “Cuvette Centrale” [Bernard, 1945] (Fig. 1). The Congo River begins its course at the Chambeshi River (Fig. 2), rising south of the Lake Tanganyika and transferred by the Bangweulu Swamps. After flowing through Lake Mweru, it joins the Lwalaba River [Balek, 1977]. The permanent surface area of Lake Bangweulu is about 3,000 km<sup>2</sup> and can expand to about 15,000 km<sup>2</sup> at the end of the rainy season when its swamps and floodplains get flooded. Lake Mweru covers about 4,650 km<sup>2</sup>, and is surrounded by permanent swamps (~1,500 km<sup>2</sup>) and floodplains (~900 km<sup>2</sup>). The Kasai River from the south, and the Ubangi River from the north are the two principal tributaries of the Congo River. Right-bank tributaries of the Congo River below its junction with the Ubangi include the Likouala aux Herbes, Sangha, Likouala and Alima rivers. Swamp forests predominate on the floodplains in this section [Beadle, 1981; Hughes *et al.*, 1992; Betbeder *et al.*, 2014]. The coupled ocean-atmosphere modes of El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are the main

159 drivers of the CRB hydro-climatic dynamics [*Saji et al.*, 1999; *Behera and Yamagata*,  
160 2001; *Reason*, 2002; *Balas et al.*, 2007; *Hastenrath et al.*, 2007]. In this study, following  
161 the drainage patterns and physical characteristics, the CRB has been divided into six sub-  
162 basins: Ubangi, Sangha, Middle-Congo, Lower-Congo, Kasai, and Lwalaba. These  
163 locations are shown in Fig. 1 and characteristics of the sub-basins are presented in Table 1.



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**Table 1. Water balance of Congo River Basin, based on [Bultot, 1971; Edwards et al., 1983; Rodier, 1983; Olivry et al., 1988; Bricquet, 1995; Mahé and Olivry, 1995; Laraque et al., 2001] (---: Insufficient data to estimate SWS)**

Basin name	Drainage area (km <sup>2</sup> )	Major rivers and lakes	Mean annual rainfall 1993-2007 (mm)	Mean annual discharge		Mean annual SWE area over 1993-2007 (km <sup>2</sup> )		SWS mean annual amplitude (km <sup>3</sup> )	Total of SWS flows out the sub-basin (%)
				location	m <sup>3</sup> /s	min	max		
<b>Ubangi</b>	651,918	<i>Uele, Bomu, Ubangi</i>	1,924	Ubangi mouth	5,936	4,785	7,648	24±4	13±2
<b>Sangha</b>	191,953	<i>Sangha, Likouala aux herbes</i>	1,950	Sangha mouth	2,471	1,752	4,668	10±2	13±2
<b>Middle congo</b>	710,758	<i>Congo, Ruki</i>	2,164	Above Ubangi	15,484	17,128	24,590	43±7	9±1
<b>Lower congo</b>	144,123	<i>From Kasai/Congo confluence to the CRB mouth</i>	1,800	Brazzaville	40,600	464	1,486	---	---
<b>Kasai</b>	884,370	<i>Kasai, Lukenie, Kwango, Lake Mai- Ndombe</i>	1,834	Lediba	11,320	10,158	13,003	28±4	8±1
<b>Lwalaba</b>	1,105,879	<i>Lomani, Lwalaba, Lake Mweru, Lake Tanganyika, Lake Bangweulu</i>	1,634	Confluence Lomani-Lwalaba	8,358	10,713 <sup>a</sup>	37,047 <sup>a</sup>	34±4	13±2
<b>TOTAL</b>	<b>3,689,001</b>	<b>CRB</b>	<b>1,842</b>	<b>Brazzaville</b>	<b>40,600</b>	<b>47,393<sup>a</sup></b>	<b>78,932<sup>a</sup></b>	<b>81±24</b>	<b>6±2</b>

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<sup>a</sup>: The constant surface of the Tanganyika Lake, around 32,600 km<sup>2</sup>, is not included.

### **3. Dataset**

#### **3.1. ENVISAT radar altimeter observations**

The ENVironmental SATellite (ENVISAT) was launched in March 2002 by the European Space Agency and its mission was ended in April 2012. The ENVISAT mission carried, among others instruments, a nadir radar altimeter [Wehr and Attema, 2001]. Along its ground tracks, repeated every 35 days, we can extract a water level time series, or “virtual stations” (VS), at each intersection with wetlands, large rivers and smaller tributaries of the CRB. The raw ENVISAT data are freely distributed by the Centre for Topographic studies of the Oceans and Hydrosphere [CTOH] in along-track Geophysical Data Records (GDRs) format. We used the ice-1 retracker [Wingham *et al.*, 1986; Bamber, 1994] as previous showed that it is the more suitable for hydrological studies in terms of accuracy of water levels and availability of the data among the commonly available retracker present in the GDRs [e.g., Frappart *et al.* 2006; Santos Da Silva *et al.* 2010]. Thus, over 2003-2009, we estimated the water level time series at 350 VS (Fig. 2) using the Virtual ALtimetry Station Tool [VALS Tool, 2009] and the Multi-mission Altimetry Processing Software (MAPS). Details about VALS and MAPS procedures can be found in Santos Da Silva *et al.* [2010] and in Frappart *et al.*, [2015a]. All 350 VS passed an efficient and reliable quality control (outlier, gap, shift). As shown in several studies [Frappart *et al.*, 2005; Santos Da Silva *et al.*, 2010; Papa *et al.*, 2012], the accuracy of altimetry derived water levels over inland water bodies is estimated to range between 10 and 40-50 cm on rivers according to the radiometric contrast between the water body and its environment within the radar footprint (vegetation, sand banks, etc ...).

#### **3.2. GIEMS surface water extent dynamics**

A globally applicable remote-sensing technique has been developed to derive wetland inundation extents: the Global Inundation Extent from Multi-Satellites (GIEMS) [Prigent

197 *et al.*, 2001, 2007, 2012, 2016, *Papa et al.*, 2006, 2010]. GIEMS merges: Microwave (19  
 198 and 37 GHz) observations from the Special Sensor Microwave/Imager (SSM/I),  
 199 backscatter at 5.25 GHz from the European Remote Sensing (ERS) scatterometer, and  
 200 visible (0.58– 0.68  $\mu\text{m}$ ) and near-infrared (0.73– 1.1  $\mu\text{m}$ ) reflectance from the Advanced  
 201 Very High Resolution Radiometer (AVHRR) to account for vegetation canopy effects  
 202 [*Papa et al.*, 2010]. GIEMS, from 1993 to 2007, provides monthly inundation percentage  
 203 at 0.25° resolution grid cells (each pixel equals 773  $\text{km}^2$ ). GIEMS dataset has been  
 204 extensively (i) evaluated at global scale [*Prigent et al.*, 2007; *Papa et al.*, 2008, 2010] and  
 205 for a broad range of environments [*Frappart et al.*, 2008; *Papa et al.*, 2008, 2013;  
 206 *Frappart et al.*, 2015b; *Papa et al.*, 2015]; and (ii) used for climatic and hydrological  
 207 studies, such as the methane surface emissions evaluation [*Bousquet et al.*, 2006; *Ringeval*  
 208 *et al.*, 2010] and the river flooding scheme validation coupled with land surface models  
 209 [*Decharme et al.*, 2008, 2011; *Getirana et al.*, 2012; *Pedinotti et al.*, 2012; *Ringeval et al.*,  
 210 2012]. Uncertainties on the inundation estimate from GIEMS is about 10% [*Prigent et al.*,  
 211 2007]. In rather densely forested regions, detection of the small areas of surface water can  
 212 be challenging [*Prigent et al.*, 2007]. This is the case within the CRB, where some regions  
 213 have very dense vegetation with a network of narrow rivers, such as in the upper part of the  
 214 Uele River in the Ubangi sub-basin and along the Lukenie and Sankuru Rivers in the Kasai  
 215 sub-basin. In these regions, when accurate VS are obtained from ENVISAT, but where  
 216 GIEMS shows limitations in properly delineating the extents of rivers and probably  
 217 underestimates small wetlands [*Prigent et al.*, 2007], we filled the missing data by  
 218 distributing 10% of water extent to each river pixel.  
 219 Note also that large freshwater bodies such as the Lake Baikal, the Great Lakes, Lake  
 220 Victoria, and more importantly here for the present study, the Lake Tanganyika, have been  
 221 masked in the GIEMS database [*Prigent et al.*, 2007]. However, its extent shows small  
 222 variations on seasonal timescale and does play an important role in the SW dynamics of the

CRB. Nevertheless, its water storage variations will be taken into account when estimating SWS variations (see Section 5).

### **3.3. Ancillary data**

#### **3.3.1. GRACE Regional Solution**

The Gravity Recovery And Climate Experiment (GRACE) mission, placed in orbit in March 2002, provides data over the continents and can be used to derive the monthly changes of the terrestrial water storage (TWS) expressed in terms of equivalent water height (EWH) [Tapley *et al.*, 2004]. In this work, we used maps of monthly TWS from the Jet Propulsion Laboratory GRACE land mascon solution (JPL RL05M, available at <http://grace.jpl.nasa.gov>). This solution proposed some improvements to reduce leakage errors i) across land/ocean boundaries using a Coastline Resolution Improvement filter and ii) for continental hydrology applications providing a set of gain factors. The description of the JPL RL05M solution in detail can be find in Watkins *et al.*, [2015] and Wiese [2015]. The dataset resolution is  $0.5^{\circ} \times 0.5^{\circ}$ , but it represents equal-area of  $3^{\circ} \times 3^{\circ}$  spherical caps. In the CRB, the measurement error dominates the leakage error, i.e 5.3 mm vs 2.7 mm respectively of EWH [Wiese *et al.*, 2016]. Over land, the scaled uncertainty derived using methods described in Wahr *et al.*, [1998] are provided and are in the range [0.7 15.8] mm of EWH over the CRB.

#### **3.3.2. Rainfall datasets**

##### **CRU TS4.00**

We used the Climatic Research Unit (CRU) Time-series (TS) version 4.00 (CRU TS4.00) [Harris *et al.*, 2014; Harris and Jones, 2017]. These data are rainfall gridded fields based on monthly observations at meteorological stations across the world's land areas and are provided on high-resolution ( $0.5 \times 0.5$  degree) grids over the period 1901-2015.

## 249 **GPCP**

250 The Global Precipitation Climatology Project (GPCP, V2.3) monthly dataset is used in this  
251 study. This dataset is computed by combining multi-satellite estimates with precipitation  
252 gauge information on 2.5° resolution grids from 1979 to present [Adler *et al.*, 2003].

## 253 **TRMM**

254 The precipitation estimates over the CRB are also obtained from the Tropical Rainfall  
255 Measuring Mission (TRMM) 3B43-v7 product [Huffman *et al.*, 2007]. This data set is  
256 available since January 1998 at 0.25°×0.25° spatial resolution and at monthly time scale.

257

### 258 **3.3.3. In situ gauge stations**

259 We use the daily discharge time series over 1993–2007 at Brazzaville (Fig. 2 15.3°E and  
260 4.3°S, Station: 1070500105 from the Direction de la Gestion des Ressources Hydrauliques  
261 (DGRH) - Brazzaville – Congo), Bangui (Fig. 2 18.6°E and 4.36°N Station: 1060700105  
262 from the Direction Générale de L'Hydraulique Service de l'Hydrologie - Bangui - Central  
263 African Republic), and Ouesso over 1993-1999 (Fig. 2 16.05°E and 1.61°N Station:  
264 1070800120 from the DGRH).

265

### 266 **3.3.4. Altimeter-derived lake height**

267 We use the time series of monthly water levels of Lake Mweru (Fig. 2, 28.5°E and 9°S)  
268 and Lake Bangweulu (Fig. 2, 29.5°E and 11°S) provided by Hydroweb  
269 (<http://www.legos.obs-mip.fr/fr/soa/hydrologie/hydroweb/>). Hydroweb is  
270 developed by the Laboratoire d'Etudes en Géophysique Océanographie Spatiales (LEGOS)  
271 in France and provides water level time series of selected water bodies (rivers, lakes,  
272 reservoirs and wetlands) worldwide using the merged data from the Topex/Poseidon,  
273 Jason-1, Jason-2, Jason-3, ERS2, ENVISAT, SARAL and Geosat Follow-On (GFO)

satellite missions. The processing procedure details of Hydroweb can be found in *Crétaux et al.*, [2011].

#### **4. Spatio-temporal variations of surface water extent (SWE)**

The mean and maximum of the SWE per grid cell over 1993 to 2007 are displayed in Figs. 3a and 3b. A very realistic spatial distribution of the major rivers (Congo, Kasai, Ubangi and Lwalaba) and some tributaries is shown by these maps. Associated inundated areas, wetlands and the region of the “Cuvette Centrale” are also well delineated. Maxima are located in two regions: (i) in the Lwalaba basin, mainly along the major lakes; and (ii) in the “Cuvette Centrale” along the Congo main stream, between 15°-18°E and 0°-2.5°S, including Lake Mai-Ndombe and Lake Tumba. The SWE and precipitation seasonal variations are presented in Fig. 4 and in Table 1. In this analysis, we computed the monthly rainfall averages over 1993-2007 from CRU TS4.00, GPCP and TRMM products. In Ubangi, Sangha and Middle Congo sub-basins, the precipitation dynamics present a bimodal distribution, which is not observed in the SWE seasonal variations. However, SWE in Ubangi and Middle Congo follow slowly the overall increase trend of precipitation from April to November. The SWE in Sangha presents a sharp increase from September to November. The SWE in these three sub-basins drops a month after the beginning of the precipitation decrease and reaches their minima 2-3 months after those of precipitation. These three sub-basins see their flooded area increase two to three-fold on average over the year. For instance, in the Middle Congo, the flooded areas vary from 16,700 km<sup>2</sup> at low waters to 26,000 km<sup>2</sup> at high waters. The SWE in Kasai shows very little variations over the year, probably due to the low GIEMS data coverage in this specific area. In the Lower Congo, between August and December, the SWE drops a month after the beginning of the precipitation decrease and reach its minimum 3 months after the precipitation minimum.

The flood period generally occurs between October and November and is perfectly in phase with the precipitation dynamics.

The SWE dynamics over 1993-2007 is also compared to: (i) the *in situ* river discharge measured at Brazzaville, Bangui and Ouessou (Fig. 5, see Fig. 2 for their locations) and (ii) satellite altimeter-derived height at Mweru, Bangweulu and Mai-Ndombe lakes (Fig. 6, see Fig. 2 for their locations). In Fig. 5, the river discharge time series of Brazzaville is compared to the total area of SWE in the “Cuvette Centrale”, i.e. [15-20°E 3-0°S] and the Bangui and Ouessou discharge time series are compared to the total area of SWE in the Ubangui and Sangha sub-basins respectively. Fig. 5 a, b, and c show that the annual variability of each river discharge time series are closely connected to the SWE dynamics, with high correlation coefficients ( $r \geq 0.8$ ). At Bangui and Ouessou, the discharge peak occurs one month before the SWE maximum.

In the following, we removed seasonal variation from the time series by using a 12-month moving average. The interannual deseasonalized anomalies of the discharge and SWE time series are presented in Fig. 5 d, e, and f. We obtain a moderate agreement ( $r > 0.5$ ) in the interannual temporal patterns between the two variables in the three locations. These SWE interannual patterns probably result in a nonlinear relationship between the discharges and other parameters of the water balance, such as groundwater levels. In addition surface water residence time could also be influenced by the size and depth of the drainage systems, and by the connection/disconnection regimes between main streams and associated inundation zones. Further investigations are needed to clarify these dynamics.

The time series of 3 lakes height variations (Mai-Ndombe, Mweru, Bangweulu) are compared in Fig. 6 with the cumulated SWE dynamics around the area. It shows that lake

height variations and the SWE are generally well correlated ( $r \geq 0.8$ , Fig. 6 a,b,c) at seasonal timescales with a delay lag of 1 and 2 months for the Bangweulu and the Mweru, respectively. At an interannual timescale, Fig 6 (d,e,f) also show high correlation ( $r \geq 0.7$ ) between the anomalies of the two variables, especially over the Mweru Lake. Over Mweru, three particular events are noticeable in 1997-1998, 2000-2001 and 2006-2007 (November to May period). Because of shorter time series, only the 2006-2007 event is noticeable for the Mai-Ndombe and Bangweulu lakes. The periods 1997-1998 and 2006-2007 are characterized by positive Indian Ocean Dipole (pIOD) events in conjunction with an El Niño event [Ummenhofer *et al.*, 2009]. In general, pIOD events induce large rainfall deficit in the eastern Indian Ocean and Indonesia, and floods in western Indian Ocean, South India, and East Africa [McPhaden, 2002]. During those events, the Mweru SWE reaches record high extent (2,700 km<sup>2</sup> and 1,900 km<sup>2</sup>) associated with large positive anomalies in the water level of the lake (Fig. 6 d and e).

In order to better characterize SWE interannual variability and its possible relation with large climate events, we further analyze the deseasonalized anomalies between 1993 and 2007 (Fig. 7). The SWE interannual variability over the Ubangi, Kasai, Middle Congo and Lower Congo show the same dynamics (Fig 7a). A large negative anomaly in SWE is observed from 1998 to 2000, which could be associated with the 1998-2000 persistent La Niña event. This type of event is often linked to drier than normal conditions over equatorial East Africa [McPhaden, 2002]. The SWE interannual variability over the Lwalaba basin (Fig. 7c) presents a large positive event in 1997/1998, previously observed in the Mweru Lake height variations (Fig. 6b/e), where a pIOD event (associated with an excess of rain in western Indian Ocean, South India, and East Africa) occurs in conjunction with an El Niño event [Ummenhofer *et al.*, 2009]. For example, after the 1997 pIOD event, the level of Lake Victoria rose by 1.7 m, Lake Tanganyika by 2.1 m and Lake Malawi by



1.8 m; the Sudd marshes levels also rose [Birkett et al., 1999; Becker et al., 2010] and very high river flows were measured at Kinshasa [Conway et al., 2005]. Moreover, these devastating floods have resulted in several thousand deaths and hundreds of thousands people have been displaced in Kenya, Somalia, Sudan, Uganda, and Ethiopia [Cai et al., 2014]. In the Lwalaba basin, the SWE increased significantly by a factor of ~4 from late 1997 to the end of 1998.

## 5. Spatio-temporal variations of surface water storage (SWS)

Here we present the spatio-temporal variability of SWS estimated by combining the SWE from GIEMS with the altimeter-derived water level heights. The two-step methodology is described briefly in the following sections and we refer to Frappart et al., [2008, 2011] for more details. The results are analyzed for 2003-2007, the common period of availability for both datasets.

### 5.1. Monthly maps of surface water level anomalies

Monthly maps of water level in the CRB were obtained by combining GIEMS and ENVISAT derived water levels. Following Frappart et al. [2008, 2011], water levels for a given month were linearly interpolated over GIEMS inundation. Each SW level map had a spatial resolution of  $0.25^\circ \times 0.25^\circ$ , and the elevation of each pixel is given with reference to a map of minimum SW levels estimated over 2003–2007 using a hypsometric approach (see Fig. S1 from Frappart et al., [2012]). For each inundated pixel of coordinates  $(\lambda_j, \varphi_j)$ , the minimum elevation is given as :

$$h_{min}(\lambda_j, \varphi_j, \alpha, \Delta T) = \min \left( h(\lambda_j, \varphi_j, t) \right)_{P(\lambda_j, \varphi_j, t) \leq \alpha; t \in \Delta T} \quad (1)$$

where  $h_{min}$  is the minimum elevation (m) during the observation period  $\Delta T$  for a percentage of inundation  $\alpha$  from GIEMS, which varies between 0 and 100 and  $t$  is a monthly observation during  $\Delta T$ .

Fig. 8 shows the seasonal evolution of surface water heights (SWH) in the CRB sub-basins for the period August 2006 to May 2007 covering a pIOD-El Niño event. In the Ubangi and Sangha basins the SWH increase in August-October (up to 4 m) and reach their maximum values in November (up to 6 meters). In the Middle Congo River Basin, SWH increase from October to December and show an important spatial variability. The SWH highest values (~3 m) are along the Congo River mainstream and in the south of the basin along the Ruki River. From January, we observe increases in the southern part of the CRB basin. In the upper Lwalaba basin we observe from January to March an important inundation zone (up to 4 m). From April, the SWH start to decline. The monthly maps of SWH are now used to estimate surface water storage expressed as volumes for 2003–2007.

## 5.2. Monthly time series of surface water volume variations

Following *Frappart et al.* [2008, 2011], the time variations of SW volume, are computed as :

$$V_{SW}(t) = R_e^2 \sum_{j \in S} P(\lambda_j, \varphi_j, t) \left( h(\lambda_j, \varphi_j, t) - h_{min}(\lambda_j, \varphi_j) \right) \cos(\varphi_j) \Delta\lambda \Delta\varphi \quad (2)$$

where  $V_{SW}$  is the volume (km<sup>3</sup>) of SW,  $R_e$  the earth's radius (6378 km),  $P(\lambda_j, \varphi_j, t)$ ,  $h(\lambda_j, \varphi_j, t)$ ,  $h_{min}(\lambda_j, \varphi_j)$  are respectively the percentage of inundation, the water level at time  $t$ , and the minimum of water level at the pixel  $(\lambda_j, \varphi_j)$ ;  $\Delta\lambda$  and  $\Delta\varphi$  are respectively the grid steps in longitude and latitude. Monthly surface water storage (SWS) fluctuations are estimated for over 2003–2007.

For lakes Bangweulu, Mai-Ndombe and Mweru, surface water volume anomalies  $\Delta V_{SW}$  were computed following Baup et al. [2014]:

$$\Delta V_{SW}(t) = S(t-1) |\Delta h(t)| + \text{sgn}(\Delta h(t)) \frac{|\Delta S(t)| |\Delta h(t)|}{2} \quad (3)$$

Where  $\Delta S(t) = S(t) - S(t-1)$  and  $\Delta h(t) = h(t) - h(t-1)$  are the variations of the surface and height of the lake between instants  $t$  and  $t-1$  respectively.

For Lake Tanganyika, anomalies of water volume were simply estimated multiplying the surface of the lake (32,600 km<sup>2</sup> from *Spigel and Coulter*, 1996) by the anomaly of water stage obtained using ENVISAT altimetry data.

The volume of SW is the sum of the contributions of the water volume contained in the floodplains and the lakes of the CRB. Accordingly, the time variations of  $TWS$  ( $V_{TWS}(t)$ ) anomalies are computed following *Ramillien et al.*, [2005]:

$$\Delta V_{TWS}(t) = R_e^2 \sum_{j \in S} \Delta h_{TWS}(\lambda_j, \varphi_j, t) \cos(\varphi_j) \Delta \lambda \Delta \varphi \quad (4)$$

where  $h_{TWS}(\lambda_j, \varphi_j, t)$  is the equivalent height anomaly of  $TWS$  (km<sup>3</sup>) at time  $t$  of the pixel of coordinates  $(\lambda_j, \varphi_j)$ ,  $R_e$  the earth's radius (6378 km),  $\Delta \lambda$  and  $\Delta \varphi$  are respectively the grid steps in longitude and latitude. The maximum error for the SW volume variation (km<sup>3</sup>),  $\Delta V$ , is estimated as :

$$\max(\Delta V) = S_{max} \Delta \delta h_{max} + \Delta S_{max} \delta h_{max} \quad (5)$$

where  $S_{max}$  is the maximum flooded surface (km<sup>2</sup>),  $\delta h_{max}$  is the maximum SWH variation (km) between two consecutive months,  $\Delta S_{max}$  is the maximum error for the flooded surface (km<sup>2</sup>) and  $\Delta \delta h_{max}$  is the maximum dispersion (km) of the SWH between two consecutive months.

Fig. 9 presents the spatial patterns of SWS changes, estimated as the year among the five years being the maximum range of SWS. It shows realistic spatial structures along the Congo River and the “Cuvette Centrale”, as well as in the Tumba and Mai-Ndombe lakes, where annual maximum storage variations reach up to 1.3 km<sup>3</sup>/year per grid cell.

425 Secondary maxima are observed in the Lwalaba basin around the lakes Kivu and  
426 Bangweulu and along the Lwalaba River upstream, with SWS varying between 0.3–0.6  
427 km<sup>3</sup>/year per grid cell. Low SWS changes are observed in other locations of CRB (below  
428 0.2 km<sup>3</sup>/year), in accordance with very low variations in water levels observed in the  
429 altimetry measurements.

430

431 To illustrate the interannual variability at the basin-scale, Fig. 10 shows the yearly  
432 variations of SWS, as a percentage of the difference from median computed 2003-2007. It  
433 reveals rather strong year-to-year and spatial variability. For instance, during the 2007  
434 pIOD/El Niño year, a clear positive anomaly of SWS is observed all over the CRB basin.  
435 During 2003, a pIOD year, increases in SWS are observed along the Ubangi river  
436 mainstream and along the north part of the Lwalaba River whereas a deficit of SWS is  
437 observed in the Kasai sub-basin. Conversely, in 2004, one notices positive anomalies of  
438 SWS of about 80-100% in the Kasai sub-basin whereas a negative anomaly is observed in  
439 the rest of CRB.

440

441 For the entire CRB over 2003-2007, on average the annual SWS amplitude is  $81 \pm 24$  km<sup>3</sup>  
442 (Fig. 11 and Table 1). A significant year-to-year variation is observed, with for instance an  
443 annual amplitude of  $\sim 57$  km<sup>3</sup> in 2003 whereas the amplitude reaches 114 km<sup>3</sup> in 2006.  
444 That corresponds to  $6 \pm 2$  % of the total fresh water volume that flows out annually from the  
445 CRB as river discharge into the Atlantic Ocean with a mean flow of  $\sim 40,600$  m<sup>3</sup>/s (i.e.  
446  $\sim 1,280$  km<sup>3</sup>/year). As a comparison, the Amazon River SWS annual variation corresponds  
447 to  $\sim 15\%$  of the total fresh water volume that flows out annually of its basin as river  
448 discharge [Frappart *et al.*, 2012]. In the Ubangi basin, the mean annual SWS amplitude  
449  $24 \pm 4$  km<sup>3</sup>, with a minimum of  $\sim 20$  km<sup>3</sup> observed in 2004 and a maximum of  $\sim 30$  km<sup>3</sup> in  
450 2007. We report an annual mean SWS amplitude of  $10 \pm 2$  km<sup>3</sup> for the Sangha and  $28 \pm 4$

km<sup>3</sup> for the Kasai. The Middle Congo presents a mean annual SWS amplitude of 43±7  
 km<sup>3</sup>, with a minimum of ~34 km<sup>3</sup> observed in 2003 and a maximum of ~52 km<sup>3</sup> in 2007. In  
 contrast, the Lwalaba basin shows an annual SWS minimum of ~30 km<sup>3</sup> observed in 2007  
 and a maximum of ~41 km<sup>3</sup> in 2005. On average this basin shows a mean annual SWS  
 amplitude of 34±4 km<sup>3</sup>, where we have included the volume variations of Bangweulu,  
 Mweru and Tanganyika Lakes obtained from the combination of altimetry and GIEMS.  
 We estimated the maximum error for the SWS change in the CRB using Equation (5) and  
 using the following values:  $S_{max} = 78\,932\text{ km}^2$  in February, 2007;  $\delta h_{max} = 0.6\text{ m}$ , mean  
 maximum SWH change between two consecutive months during 2003-2007;  $\Delta S_{max} = 10\%$   
 from *Prigent et al.*, [2007] of  $78\,932\text{ km}^2$ ; and  $\Delta \delta h_{max} = 0.2\text{ m}$ , maximum average  
 dispersion of the SWH in 2007. We obtain a maximum error of ~20 km<sup>3</sup> for an annual  
 variation of 76 km<sup>3</sup> in 2007, i.e., an error of ~26%. This value is of the same order of  
 magnitude as that obtained over the Rio Negro (~23% *Frappart et al.*, [2008]), over the  
 Orinoco Basin (~30%, *Frappart et al.*, [2015b]) and over the Ganges-Brahmaputra Basin  
 (~24%, *Papa et al.*, [2015]). In the same way, we obtained over the sub-basins the  
 maximum errors of ~17% for the Ubangui, ~23% for the Sangha, ~17% for the Middle  
 Congo, ~19% over the Kasai, and ~27% over the Lwalaba. Respectively, the mean annual  
 variation in SWS represents 13±2 % of the total volume of water that flows out the Ubangi  
 basin and at the Sangha mouth, 8±1 % at the Kasai mouth, 9±1 % along the Congo River  
 above the Ubangi mouth and ~13±2% at the Lwalaba mouth.

In Fig 11, we compared the SWS and TWS from the GRACE solution. For the entire CRB,  
 the correlation between the SWS and TWS is ~0.8 and the SWS preceded TWS by one  
 month. The seasonal SWS variations, estimated as the ratio between the mean amplitude of  
 SWS and TWS variations over the study period, represent 10±1 % of the TWS variations  
 in the Ubangi basin, 18±1% in the Sangha, 33±7 % in the Middle Congo, encompassing

extensive floodplains and Lake Tumba, and  $12 \pm 2$  % in the Lwalaba sub-basins. For the entire CRB, the seasonal SWS variations represent  $19 \pm 5$  % of the TWS variations. As a comparison, using the same approach, the seasonal contribution of SWS to TWS variations were found to be of  $\sim 43\%$  for the Amazon [Frappart *et al.*, 2012] and 45% in the Ganges-Brahmaputra basin [Papa *et al.*, 2015].

We subtract SWS to TWS in order to obtain the “sub-surface water storage” variations (Sub-SWS, Fig.11) defined as the sum of soil moisture and groundwater. We assume that the variations in water storage compartments derived from canopy are negligible over the 2003-2007 in the CRB and hence are not considered here. The Sub-SWS contribution (Fig.11) in the Ubangi, Sangha and Lwalaba basins is very important and suggests that the hydrological compartments, such as soil moisture and groundwater, have a major influence on TWS. On the contrary, in the Middle Congo, the SWS alone contributes over one-third of the TWS variations over this sub-basin.

## 6. Conclusions and perspectives

This work presents an unparalleled analysis of the dynamics of surface water extent (1993–2007) and storage (2003-2007) in the CRB. First, we show that the SWE seasonal patterns from GIEMS dataset exhibit very realistic distributions of major rivers (Congo, Kasai, Ubangi and Lwalaba) and their tributaries, with two maxima located: i) in the lake region of the Lwalaba sub-basin and ii) in the “Cuvette Centrale”, including Tumba and Mai-Ndombe Lakes. For the period 1993-2007, we found a ENSO/IOD influence on the SWE interannual variability. Following the approach developed by Frappart *et al.* [2008, 2011], we combined GIEMS observations with inland water level variations from ENVISAT radar altimetry (350 observations on the rivers) to analyze the variations of fresh water stored in the CRB different hydrological compartments. Overall, during 2003-2007, the

annual mean variation in SWS was  $81 \pm 24 \text{ km}^3$  and contributes to  $19 \pm 5 \%$  of the annual variations of GRACE-derived TWS. It represents also  $6 \pm 2 \%$  of the annual fresh water volume that flows from the CRB into the Atlantic Ocean. Finally, we can mention the very different behavior in the Middle Congo River Basin, where SWS alone contributes more than one-third of the TWS variations over this sub-basin. It is important to note that the spatial-resolution sampling of the altimetry-based virtual station dataset could be increased using ENVISAT and ERS archives, especially with the recent reprocessing devoted land water studies made available by CTOH [Frappart *et al.*, 2016] and temporal extended using current altimetry satellites including Jason-1 (GDR E), Jason-2, Jason-3, SARAL, and Sentinel-3A, as well as future missions such as Sentinel-3B (to be launched in 2017), Sentinel-6/Jason-CS (Jason-CS A and B planned for 2020 and 2026, respectively). This new surface water storage (and sub-surface water storage) dataset for the CRB over 5 years is a further step towards improving our knowledge of climatic and hydrological processes in this region. This new surface water storage (and sub-surface water storage) dataset for the CRB over 5 years is a further step towards improving our knowledge of climatic and hydrological processes in this region. It is an unprecedented source of information for hydrological modeling of the CRB as well as a baseline in the definition and validation of future hydrology-oriented satellite missions such as the NASA-CNES Surface Water Ocean Topography (SWOT) to be launched in 2021, which will be dedicated to global surface hydrology. More generally, these results on the large scale CRB's hydro-climate processes, in addition to improving our fundamental knowledge about this major hydrologic basin, offer an unique opportunity for conducting many new studies in Africa by using even larger datasets, with a focus on a clear gain for the management of water resources in this continent.

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## 532 **References**

- 533 Achard, F., H. D. Eva, H.-J. Stibig, P. Mayaux, J. Gallego, T. Richards, and J.-P. Malingreau (2002),  
534 Determination of deforestation rates of the world’s humid tropical forests, *Science*, 297(5583), 999–1002.
- 535 Adler, R. F. et al. (2003), The version-2 global precipitation climatology project (GPCP) monthly  
536 precipitation analysis (1979–present), *Journal of hydrometeorology*, 4(6), 1147–1167.
- 537 Alsdorf, D., E. Beighley, A. Laraque, H. Lee, R. Tshimanga, F. O’Loughlin, G. Mahe, D. Bienvenu, G.  
538 Moukandi, and R. G. M. Spencer (2016), Opportunities for Hydrologic Research in the Congo Basin, *Rev.*  
539 *Geophys.*, 2016RG000517, doi:10.1002/2016RG000517.
- 540 Alsdorf, D. E., E. Rodríguez, and D. P. Lettenmaier (2007), Measuring surface water from space, *Reviews of*  
541 *Geophysics*, 45(2), doi:10.1029/2006RG000197.
- 542 Balas, N., S. E. Nicholson, and D. Klotter (2007), The relationship of rainfall variability in West Central  
543 Africa to sea-surface temperature fluctuations, *International journal of climatology*, 27(10), 1335–1349.
- 544 Balek, J. (1977), *Hydrology and water resources in tropical Africa*, Elsevier.
- 545 Bamber, J. L. (1994), Ice sheet altimeter processing scheme, *International Journal of Remote Sensing*, 15(4),  
546 925–938, doi:10.1080/01431169408954125.
- 547 Baup, F., F. Frappart, and J. Maubant (2014), Combining high-resolution satellite images and altimetry to  
548 estimate the volume of small lakes, *Hydrol. Earth Syst. Sci.*, 18(5), 2007–2020, doi:10.5194/hess-18-2007-  
549 2014.
- 550 Beadle, L. C. (1981), *The inland waters of Africa. An introduction to tropical limnology*, Longman, London.
- 551 Becker, M., W. L. Lovel, A. Cazenave, A. Güntner, and J.-F. Crétaux (2010), Recent hydrological behavior of  
552 the East African great lakes region inferred from GRACE, satellite altimetry and rainfall observations,  
553 *Comptes Rendus Geoscience*, 342(3), 223–233.
- 554 Becker, M., J. da Silva, S. Calmant, V. Robinet, L. Linguet, and F. Seyler (2014), Water Level Fluctuations  
555 in the Congo Basin Derived from ENVISAT Satellite Altimetry, *Remote Sensing*, 6(10), 9340–9358,  
556 doi:10.3390/rs6109340.
- 557 Behera, S. K., and T. Yamagata (2001), Subtropical SST dipole events in the southern Indian Ocean,  
558 *Geophys. Res. Lett.*, 28(2), 327–330, doi:10.1029/2000GL011451.
- 559 Beighley, R. E., R. L. Ray, Y. He, H. Lee, L. Schaller, K. M. Andreadis, M. Durand, D. E. Alsdorf, and C. K.  
560 Shum (2011), Comparing satellite derived precipitation datasets using the Hillslope River Routing (HRR)  
561 model in the Congo River Basin, *Hydrological Processes*, 25(20), 3216–3229.
- 562 Bele, Y., E. Mulotwa, B. Bokoto de Semboli, D. Sonwa, and A. M. Tiani (2010), Central Africa: the effects  
563 of climate change in the Congo Basin; the need to support local adaptive capacity,
- 564 Bernard, É. (1945), *Le climat écologique: de la cuvette centrale congolaise*.
- 565 Betbeder, J., V. Gond, F. Frappart, N. N. Baghdadi, G. Briant, and E. Bartholome (2014), Mapping of  
566 Central Africa Forested Wetlands Using Remote Sensing, *IEEE Journal of Selected Topics in Applied Earth*  
567 *Observations and Remote Sensing*, 7(2), 531–542, doi:10.1109/JSTARS.2013.2269733.
- 568 Birkett, C., R. Murtugudde, and T. Allan (1999), Indian Ocean climate event brings floods to East Africa’s  
569 lakes and the Sudd Marsh, *Geophysical Research Letters*, 26(8), 1031–1034.
- 570 Birkett, C. M. (1995), The contribution of TOPEX/POSEIDON to the global monitoring of climatically  
571 sensitive lakes, *Journal of Geophysical Research: Oceans*, 100(C12), 25179–25204.
- 572 Bousquet, P. et al. (2006), Contribution of anthropogenic and natural sources to atmospheric methane  
573 variability, *Nature*, 443(7110), 439–443, doi:10.1038/nature05132.
- 574 Bricquet, J.-P. (1995), Les écoulements du Congo à Brazzaville et la spatialisation des apports, in *Grands*



575 *bassins fluviaux périatlantiques : Congo, Niger, Amazone*, edited by J. Boulègue, J.-C. Olivry, and Grands  
576 Bassins Fluviaux Péri-Atlantiques : Congo, Niger, Amazone, Paris (FRA), 1993/11/22-24, pp. 27–38,  
577 ORSTOM, Paris.

578 Brown, H. C. P., B. Smit, O. A. Somorin, D. J. Sonwa, and J. N. Nkem (2014), Climate change and forest  
579 communities: prospects for building institutional adaptive capacity in the Congo Basin forests, *Ambio*, 43(6),  
580 759–769.

581 Bultot, F. (1971), *Atlas climatique du bassin congolais*, INEAC.

582 Bwangoy, J.-R. B., M. C. Hansen, D. P. Roy, G. D. Grandi, and C. O. Justice (2010), Wetland mapping in  
583 the Congo Basin using optical and radar remotely sensed data and derived topographical indices, *Remote*  
584 *Sensing of Environment*, 114(1), 73–86, doi:10.1016/j.rse.2009.08.004.

585 Cai, W., A. Santoso, G. Wang, E. Weller, L. Wu, K. Ashok, Y. Masumoto, and T. Yamagata (2014),  
586 Increased frequency of extreme Indian Ocean Dipole events due to greenhouse warming, *Nature*, 510(7504),  
587 254–258, doi:10.1038/nature13327.

588 Calmant, S., F. Seyler, and J. F. Cretaux (2008), Monitoring continental surface waters by satellite altimetry,  
589 *Surveys in geophysics*, 29(4–5), 247–269.

590 Camberlin, P., S. Janicot, and I. Poccarrd (2001), Seasonality and atmospheric dynamics of the teleconnection  
591 between African rainfall and tropical sea-surface temperature: Atlantic vs. ENSO, *International Journal of*  
592 *Climatology*, 21(8), 973–1005.

593 Conway, D., E. Allison, R. Felstead, and M. Goulden (2005), Rainfall variability in East Africa: implications  
594 for natural resources management and livelihoods, *Philosophical Transactions of the Royal Society of*  
595 *London A: Mathematical, Physical and Engineering Sciences*, 363(1826), 49–54.

596 Crétaux, J.-F., and C. Birkett (2006), Lake studies from satellite radar altimetry, *Comptes Rendus*  
597 *Geoscience*, 338(14), 1098–1112.

598 Crétaux, J.-F., S. Calmant, R. A. Del Rio, A. Kouraev, M. Bergé-Nguyen, and P. Maisongrande (2011),  
599 Lakes studies from satellite altimetry, in *Coastal Altimetry*, pp. 509–533, Springer.

600 Crétaux, J.-F., R. Abarca-del-Río, M. Berge-Nguyen, A. Arsen, V. Drolon, G. Clos, and P. Maisongrande  
601 (2016), Lake Volume Monitoring from Space, *Surveys in Geophysics*, 37(2), 269–305.

602 Crowley, J. W., J. X. Mitrovica, R. C. Bailey, M. E. Tamisiea, and J. L. Davis (2006), Land water storage  
603 within the Congo Basin inferred from GRACE satellite gravity data, *Geophysical Research Letters*, 33(19),  
604 L19402.

605 CTOH (n.d.), Center for Topographic studies of the Ocean and Hydrosphere., Available from:  
606 <http://ctoh.legos.obs-mip.fr/> (Accessed 26 April 2016)

607 Dargie, G. C., S. L. Lewis, I. T. Lawson, E. T. Mitchard, S. E. Page, Y. E. Bockko, and S. A. Ifo (2017), Age,  
608 extent and carbon storage of the central Congo Basin peatland complex, *Nature*.

609 Decharme, B., H. Douville, C. Prigent, F. Papa, and F. Aires (2008), A new river flooding scheme for global  
610 climate applications: Off-line evaluation over South America, *J. Geophys. Res.*, 113(D11), D11110,  
611 doi:10.1029/2007JD009376.

612 Decharme, B., R. Alkama, F. Papa, S. Faroux, H. Douville, and C. Prigent (2011), Global off-line evaluation  
613 of the ISBA-TRIP flood model, *Clim Dyn*, 38(7–8), 1389–1412, doi:10.1007/s00382-011-1054-9.

614 Edwards, K. A., G. A. Classen, E. H. J. Schrotten, and others (1983), The water resource in tropical Africa  
615 and its exploitation,

616 Frappart, F., F. Seyler, J.-M. Martinez, J. G. León, and A. Cazenave (2005), Floodplain water storage in the  
617 Negro River basin estimated from microwave remote sensing of inundation area and water levels, *Remote*  
618 *Sensing of Environment*, 99(4), 387–399, doi:10.1016/j.rse.2005.08.016.

619 Frappart, F., S. Calmant, M. Cauhopé, F. Seyler, and A. Cazenave (2006), Preliminary results of ENVISAT  
620 RA-2-derived water levels validation over the Amazon basin, *Remote Sensing of Environment*, 100(2), 252–  
621 264, doi:10.1016/j.rse.2005.10.027.

622 Frappart, F., F. Papa, J. S. Famiglietti, C. Prigent, W. B. Rossow, and F. Seyler (2008), Interannual variations  
623 of river water storage from a multiple satellite approach: A case study for the Rio Negro River basin, *Journal*  
624 *of Geophysical Research: Atmospheres*, 113(D21).

625 Frappart, F., F. Papa, A. Güntner, W. Susanna, G. Ramillien, C. Prigent, W. B. Rossow, and M.-P. Bonnet

626 (2010), Interannual variations of the terrestrial water storage in the Lower Ob'Basin from a multisatellite  
627 approach, *Hydrology and Earth System Sciences Discussions*, 14(12), 2443–2453.

628 Frappart, F. et al. (2011), Satellite-based estimates of groundwater storage variations in large drainage basins  
629 with extensive floodplains, *Remote Sensing of Environment*, 115(6), 1588–1594,  
630 doi:10.1016/j.rse.2011.02.003.

631 Frappart, F., F. Papa, J. S. da Silva, G. Ramillien, C. Prigent, F. Seyler, and S. Calmant (2012), Surface  
632 freshwater storage and dynamics in the Amazon basin during the 2005 exceptional drought, *Environ. Res.*  
633 *Lett.*, 7(4), 044010, doi:10.1088/1748-9326/7/4/044010.

634 Frappart, F., F. Papa, V. Marieu, Y. Malbeteau, F. Jordy, S. Calmant, F. Durand, and S. Bala (2015a),  
635 Preliminary Assessment of SARAL/AltiKa Observations over the Ganges-Brahmaputra and Irrawaddy  
636 Rivers, *Marine Geodesy*, 38(sup1), 568–580, doi:10.1080/01490419.2014.990591.

637 Frappart, F., F. Papa, Y. Malbeteau, J. G. León, G. Ramillien, C. Prigent, L. Seoane, F. Seyler, and S.  
638 Calmant (2015b), Surface Freshwater Storage Variations in the Orinoco Floodplains Using Multi-Satellite  
639 Observations, *Remote Sensing*, 7(1), 89–110.

640 Frappart, F., B. Legrésy, F. Nino, F. Blarel, N. Fuller, S. Fleury, F. Birol, and S. Calmant (2016), An ERS-2  
641 altimetry reprocessing compatible with ENVISAT for long-term land and ice sheets studies, *Remote Sensing*  
642 *of Environment*, 184, 558–581.

643 Getirana, A. C. V., A. Boone, D. Yamazaki, B. Decharme, F. Papa, and N. Mognard (2012), The  
644 Hydrological Modeling and Analysis Platform (HyMAP): Evaluation in the Amazon Basin, *J. Hydrometeor.*,  
645 13(6), 1641–1665, doi:10.1175/JHM-D-12-021.1.

646 Harris, I., P. D. Jones, T. J. Osborn, and D. H. Lister (2014), Updated high-resolution grids of monthly  
647 climatic observations - the CRU TS3.10 Dataset: UPDATED HIGH-RESOLUTION GRIDS OF MONTHLY  
648 CLIMATIC OBSERVATIONS, *International Journal of Climatology*, 34(3), 623–642,  
649 doi:10.1002/joc.3711.

650 Harris, I. C., and P. D. Jones (2017), CRU TS4.00: Climatic Research Unit (CRU) Time-Series (TS) version  
651 4.00 of high resolution gridded data of month-by-month variation in climate (Jan. 1901- Dec. 2015). Centre  
652 for Environmental Data Analysis., *University of East Anglia Climatic Research Unit*,  
653 doi:10.5072/edf8febfdad48abb2cbaf7d7e846a86.

654 Hastenrath, S. (1985), *Climate and circulation of the tropics*, Springer Netherlands, Dordrecht.

655 Hastenrath, S., D. Polzin, and C. Mutai (2007), Diagnosing the 2005 drought in equatorial East Africa.,  
656 *Journal of Climate*, 20(18).

657 Huffman, G. J., R. F. Adler, D. T. Bolvin, G. Gu, E. J. Nelkin, K. P. Bowman, Y. Hong, E. F. Stocker, and D.  
658 B. Wolff (2007), The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear,  
659 combined-sensor precipitation estimates at fine scales., *Journal of Hydrometeorology*, 8(1).

660 Hughes, R. H., J. S. Hughes, and G. M. Bernacsek (1992), *A directory of African wetlands*, IUCN.

661 Jung, H. C., J. Hamski, M. Durand, D. Alsdorf, F. Hossain, H. Lee, A. K. M. Hossain, K. Hasan, A. S. Khan,  
662 and A. K. M. Hoque (2010), Characterization of complex fluvial systems using remote sensing of spatial and  
663 temporal water level variations in the Amazon, Congo, and Brahmaputra Rivers, *Earth Surface Processes*  
664 *and Landforms*, 35(3), 294–304.

665 Laraque, A., G. Mahé, D. Orange, and B. Marieu (2001), Spatiotemporal variations in hydrological regimes  
666 within Central Africa during the XXth century, *Journal of Hydrology*, 245(1), 104–117.

667 Laraque, A., J. P. Bricquet, A. Pandi, and J. C. Olivry (2009), A review of material transport by the Congo  
668 River and its tributaries, *Hydrological processes*, 23(22), 3216–3224.

669 Lee, H., R. E. Beighley, D. Alsdorf, H. C. Jung, C. K. Shum, J. Duan, J. Guo, D. Yamazaki, and K.  
670 Andreadis (2011), Characterization of terrestrial water dynamics in the Congo Basin using GRACE and  
671 satellite radar altimetry, *Remote Sensing of Environment*, 115(12), 3530–3538.

672 Lee, H., H. C. Jung, T. Yuan, R. E. Beighley, and J. Duan (2014), Controls of terrestrial water storage  
673 changes over the central Congo Basin determined by integrating PALSAR ScanSAR, Envisat altimetry, and  
674 GRACE data, *Remote Sensing of the Terrestrial Water Cycle*, 206, 117.

675 Lee, H., T. Yuan, H. C. Jung, and E. Beighley (2015), Mapping wetland water depths over the central Congo  
676 Basin using PALSAR ScanSAR, Envisat altimetry, and MODIS VCF data, *Remote Sensing of Environment*,  
677 159, 70–79.

- 678 Mahé, G., and J.-C. Olivry (1995), Variations des précipitations et des écoulements en Afrique de l'Ouest et  
679 centrale de 1951 à 1989, *Science et changements planétaires/Sécheresse*, 6(1), 109–117.
- 680 Mahé, G., and J.-C. Olivry (1999), assessment of freshwater yields to the ocean along the intertropical  
681 Atlantic coast of Africa (1951–1989), *Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and*  
682 *Planetary Science*, 328(9), 621–626.
- 683 McPhaden, M. J. (2002), El Ni no and La Ni na: Causes and Global Consequences, *Encyclopedia of global*  
684 *environmental change*, 1, 1–17.
- 685 Olivier, J., G. Janssens-Maenhout, M. Muntean, and J. Peters (2016), *Trends in global CO2 emissions; 2016*  
686 *Report*, The Hague: PBL Netherlands Environmental Assessment Agency; Brussels: Joint Research Centre.
- 687 Olivry, J.-C., J.-P. Bricquet, J.-P. Thiébaux, L. Sighe-Nkamdjou, and Sediment Budgets : Symposium, Porto-  
688 Alegre (BRA), 1988/12 (1988), Transport de matière sur les grands fleuves des régions intertropicales : les  
689 premiers résultats des mesures de flux particulières sur le bassin du fleuve Congo, in *Sediment budgets*, vol.  
690 174, pp. 509–521, AISH, Wallingford.
- 691 O'Loughlin, F., M. A. Trigg, G.-P. Schumann, and P. D. Bates (2013), Hydraulic characterization of the  
692 middle reach of the Congo River, *Water Resources Research*, 49(8), 5059–5070.
- 693 Papa, F., C. Prigent, F. Durand, and W. B. Rossow (2006), Wetland dynamics using a suite of satellite  
694 observations: A case study of application and evaluation for the Indian Subcontinent, *Geophys. Res. Lett.*,  
695 33(8), L08401, doi:10.1029/2006GL025767.
- 696 Papa, F., A. Güntner, F. Frappart, C. Prigent, and W. B. Rossow (2008), Variations of surface water extent  
697 and water storage in large river basins: A comparison of different global data sources, *Geophysical Research*  
698 *Letters*, 35(11).
- 699 Papa, F., C. Prigent, F. Aires, C. Jimenez, W. B. Rossow, and E. Matthews (2010), Interannual variability of  
700 surface water extent at the global scale, 1993–2004, *Journal of Geophysical Research: Atmospheres*,  
701 115(D12).
- 702 Papa, F., S. K. Bala, R. K. Pandey, F. Durand, V. V. Gopalakrishna, A. Rahman, and W. B. Rossow (2012),  
703 Ganga-Brahmaputra river discharge from Jason-2 radar altimetry: An update to the long-term satellite-  
704 derived estimates of continental freshwater forcing flux into the Bay of Bengal, *J. Geophys. Res.*, 117(C11),  
705 C11021, doi:10.1029/2012JC008158.
- 706 Papa, F., F. Frappart, A. Güntner, C. Prigent, F. Aires, A. C. Getirana, and R. Maurer (2013), Surface  
707 freshwater storage and variability in the Amazon basin from multi-satellite observations, 1993–2007, *Journal*  
708 *of Geophysical Research: Atmospheres*, 118(21), 11–951.
- 709 Papa, F. et al. (2015), Satellite-derived surface and sub-surface water storage in the Ganges–Brahmaputra  
710 River Basin, *Journal of Hydrology: Regional Studies*.
- 711 Pedinotti, V., A. Boone, B. Decharme, J. F. Crétaux, N. Mognard, G. Panthou, F. Papa, and B. A. Tanimoun  
712 (2012), Evaluation of the ISBA-TRIP continental hydrologic system over the Niger basin using in situ and  
713 satellite derived datasets, *Hydrol. Earth Syst. Sci.*, 16(6), 1745–1773, doi:10.5194/hess-16-1745-2012.
- 714 Prigent, C., E. Matthews, F. Aires, and W. B. Rossow (2001), Remote sensing of global wetland dynamics  
715 with multiple satellite data sets, *Geophys. Res. Lett.*, 28(24), 4631–4634, doi:10.1029/2001GL013263.
- 716 Prigent, C., F. Papa, F. Aires, W. B. Rossow, and E. Matthews (2007), Global inundation dynamics inferred  
717 from multiple satellite observations, 1993–2000, *J. Geophys. Res.*, 112(D12), D12107,  
718 doi:10.1029/2006JD007847.
- 719 Prigent, C., F. Papa, F. Aires, C. Jimenez, W. B. Rossow, and E. Matthews (2012), Changes in land surface  
720 water dynamics since the 1990s and relation to population pressure: LAND SURFACE WATER  
721 DYNAMICS, *Geophysical Research Letters*, 39(8), n/a-n/a, doi:10.1029/2012GL051276.
- 722 Prigent, C., D. P. Lettenmaier, F. Aires, and F. Papa (2016), Toward a high-resolution monitoring of  
723 continental surface water extent and dynamics, at global scale: from GIEMS (Global Inundation Extent from  
724 Multi-Satellites) to SWOT (Surface Water Ocean Topography), *Surveys in Geophysics*, 37(2), 339–355.
- 725 Ramillien, G., F. Frappart, A. Cazenave, and A. Güntner (2005), Time variations of land water storage from  
726 an inversion of 2 years of GRACE geoids, *Earth and Planetary Science Letters*, 235(1–2), 283–301,  
727 doi:10.1016/j.epsl.2005.04.005.
- 728 Reason, C. J. C. (2002), Sensitivity of the southern African circulation to dipole sea-surface temperature  
729 patterns in the south Indian Ocean, *International Journal of Climatology*, 22(4), 377–393.

730 Ringeval, B., N. de Noblet-Ducoudré, P. Ciais, P. Bousquet, C. Prigent, F. Papa, and W. B. Rossow (2010),  
731 An attempt to quantify the impact of changes in wetland extent on methane emissions on the seasonal and  
732 interannual time scales: WETLAND EXTENT'S CHANGES AND CH<sub>4</sub> EMISSIONS, *Global*  
733 *Biogeochemical Cycles*, 24(2), n/a-n/a, doi:10.1029/2008GB003354.

734 Ringeval, B. et al. (2012), Modelling sub-grid wetland in the ORCHIDEE global land surface model:  
735 evaluation against river discharges and remotely sensed data, *Geosci. Model Dev.*, 5(4), 941–962,  
736 doi:10.5194/gmd-5-941-2012.

737 Rodier, J. (1983), Hydrology of humid tropical regions,

738 Rosenqvist, \AA, and C. M. Birkett (2002), Evaluation of JERS-1 SAR mosaics for hydrological applications  
739 in the Congo river basin, *International Journal of Remote Sensing*, 23(7), 1283–1302.

740 Saji, N. H., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata (1999), A dipole mode in the tropical  
741 Indian Ocean, *Nature*, 401(6751), 360–363.

742 Samba, G., and D. Nganga (2012), Rainfall variability in Congo-Brazzaville: 1932–2007, *International*  
743 *Journal of Climatology*, 32(6), 854–873.

744 Samba, G., D. Nganga, and M. Mpounza (2008), Rainfall and temperature variations over Congo-Brazzaville  
745 between 1950 and 1998, *Theoretical and Applied Climatology*, 91(1), 85–97.

746 Santos Da Silva, J., S. Calmant, F. Seyler, O. C. Rotunno Filho, G. Cochonneau, and W. J. Mansur (2010),  
747 Water levels in the Amazon basin derived from the ERS 2 and ENVISAT radar altimetry missions, *Remote*  
748 *Sensing of Environment*, 114(10), 2160–2181, doi:10.1016/j.rse.2010.04.020.

749 Spigel, R. H., and G. W. Coulter (1996), Comparison of hydrology and physical limnology of the East  
750 African great lakes: Tanganyika, Malawi, Victoria, Kivu and Turkana (with reference to some North  
751 American Great Lakes), *The limnology, climatology and paleoclimatology of the East African lakes*, 103–  
752 139.

753 Tapley, B. D., S. Bettadpur, M. Watkins, and C. Reigber (2004), The gravity recovery and climate  
754 experiment: Mission overview and early results, *Geophys. Res. Lett.*, 31(9), L09607,  
755 doi:10.1029/2004GL019920.

756 Tshimanga, R. M., and D. A. Hughes (2012), Climate change and impacts on the hydrology of the Congo  
757 Basin: The case of the northern sub-basins of the Oubangui and Sangha Rivers, *Physics and Chemistry of the*  
758 *Earth, Parts A/B/C*, 50–52, 72–83, doi:10.1016/j.pce.2012.08.002.

759 Tshimanga, R. M., D. A. Hughes, and E. Kapangaziwiri (2011), Initial calibration of a semi-distributed  
760 rainfall runoff model for the Congo River basin, *Physics and Chemistry of the Earth, Parts A/B/C*, 36(14),  
761 761–774.

762 Ummenhofer, C. C., M. H. England, P. C. McIntosh, G. A. Meyers, M. J. Pook, J. S. Risbey, A. S. Gupta,  
763 and A. S. Taschetto (2009), What causes southeast Australia's worst droughts?, *Geophysical Research*  
764 *Letters*, 36(4).

765 VALS Tool (2009), Virtual ALtimetry Station. Version 0.5.7.,

766 Verhegghen, A., P. Mayaux, C. De Wasseige, and P. Defourny (2012), Mapping Congo Basin vegetation  
767 types from 300 m and 1 km multi-sensor time series for carbon stocks and forest areas estimation,  
768 *Biogeosciences*, 9(12), 5061.

769 Wahr, J., M. Molenaar, and F. Bryan (1998), Time variability of the Earth's gravity field: Hydrological and  
770 oceanic effects and their possible detection using GRACE, *Journal of Geophysical Research: Solid Earth*,  
771 103(B12), 30205–30229.

772 Watkins, M. M., D. N. Wiese, D.-N. Yuan, C. Boening, and F. W. Landerer (2015), Improved methods for  
773 observing Earth's time variable mass distribution with GRACE using spherical cap mascons, *Journal of*  
774 *Geophysical Research: Solid Earth*, 120(4), 2648–2671.

775 Wehr, T., and E. Attema (2001), Geophysical validation of ENVISAT data products, *Advances in Space*  
776 *Research*, 28(1), 83–91.

777 Wiese, D. N. (2015), GRACE MASCON Ocean and Hydrology Equivalent Water Heights JPL RL05M.1, ,  
778 doi:10.5067/TEMSC-OCL05.

779 Wiese, D. N., F. W. Landerer, and M. M. Watkins (2016), Quantifying and reducing leakage errors in the  
780 JPL RL05M GRACE mascon solution, *Water Resources Research*, 52(9), 7490–7502.

781 Wingham, D. J., C. G. Rapley, and Griffiths, H. (1986), New Techniques in Satellite Tracking Systems,  
782 *IGARSS '86 Symposium Digest, I*, 185–190.

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785

786 **Figure captions:**

787 Fig. 1. The Congo River Basin: topography and the major sub-catchment areas.

788 Fig. 2. Location of the 350 ENVISAT radar altimeter virtual stations (black dots). Location  
789 of the in situ discharge stations (Brazzaville, Bangui and Ouessou) displayed with red  
790 triangles. Lakes are: 1. Tumba, 2. Mai-Ndombe, 3. Kivu, 4. Tanganyika, 5. Mweru and 6.  
791 Bangweulu. The locations of the four lakes using in the study are displayed with diamonds  
792 (Mai-Ndombe, Mweru, Tangkanyika and Bangweulu). Countries are AO: Angola; BU:  
793 Burundi; CT: Central African Republic; DC: Democratic Republic of the Congo; RC:  
794 Republic of the Congo; RW: Rwanda; SS: South Sudan; TZ: Tanzania; UG: Uganda; ZA:  
795 Zambia;

796 Fig. 3. Inundation extent from GIEMS over the Congo basin. Spatial distribution of the (a)  
797 monthly mean and (b) monthly maximum surface water extent averaged over 1993–2007,  
798 for each 773 km<sup>2</sup> pixel.

799 Fig. 4. Surface water extent seasonal variations (SWE, black) and rainfall average (blue)  
800 over 1993–2007 by sub-basins. The shaded areas depict the standard deviations around the  
801 SWE and rainfall average.

802 Fig. 5. Comparison of annual and interannual monthly mean surface water extent  
803 anomalies (SWE, black) and in-situ monthly mean discharge anomalies (Discharge, blue)  
804 at Brazzaville, Bangui, and Ouessou locations.

805 Fig. 6. Comparison of annual and interannual monthly mean surface water extent  
806 anomalies (SWE, black) and altimetry monthly mean water height anomalies (Height,  
807 blue) of Mweru, Bangweulu, and Mai-Ndombe lakes.

808 Fig. 7. Interannual monthly mean surface water extent (SWE) anomalies by sub-basins  
809 over 1993–2007.

810 Fig. 8. Seasonal evolution of the surface water heights (SWH) in meters.

811 Fig. 9. Maximum annual surface water storage (SWS) amplitudes in km<sup>3</sup> over 2003 to  
812 2007.

813 Fig. 10. Percentage of surface water storage (SWS) variations per year over 2003 to 2007.

814 Fig. 11. Anomalies of surface water storage (SWS, black line), the GRACE-derived  
815 terrestrial water storage (TWS, blue line) and the resulting sub-surface water storage (Sub-  
816 SWS, red line) for the entire Congo River Basin and for the sub-basins.

**Fig.1**

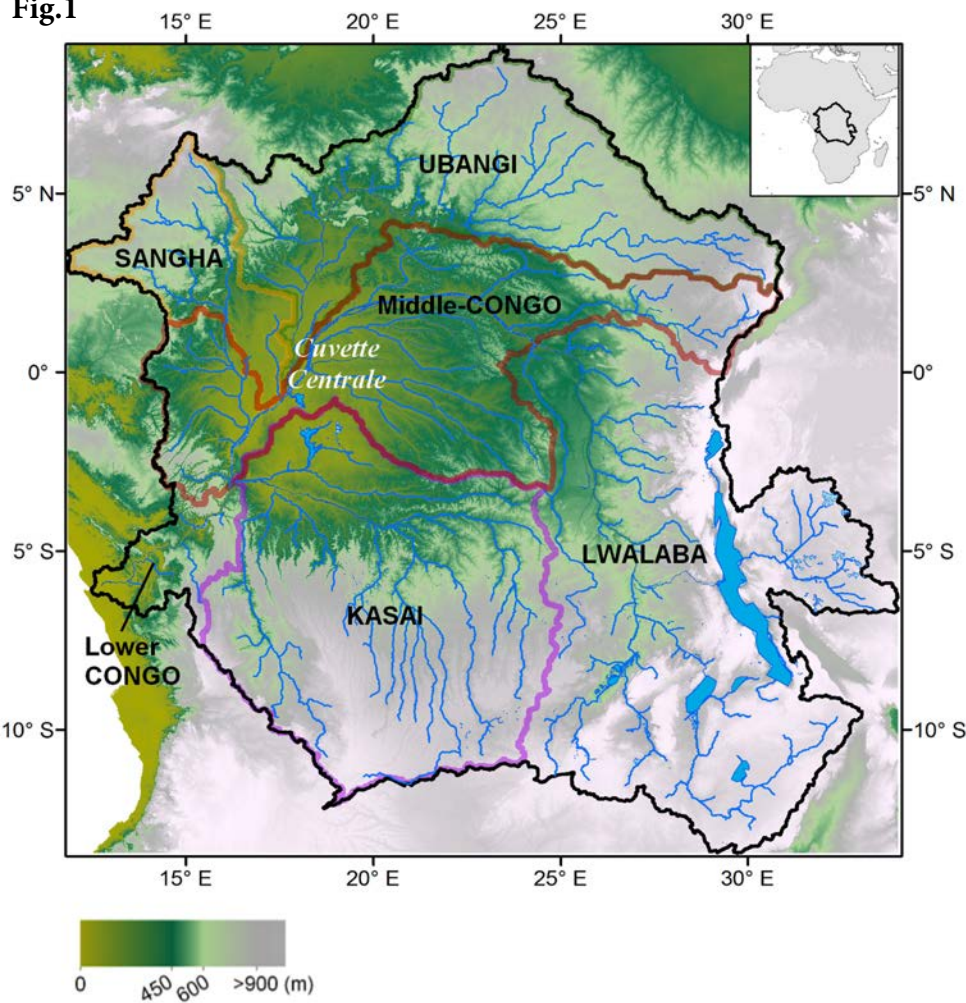
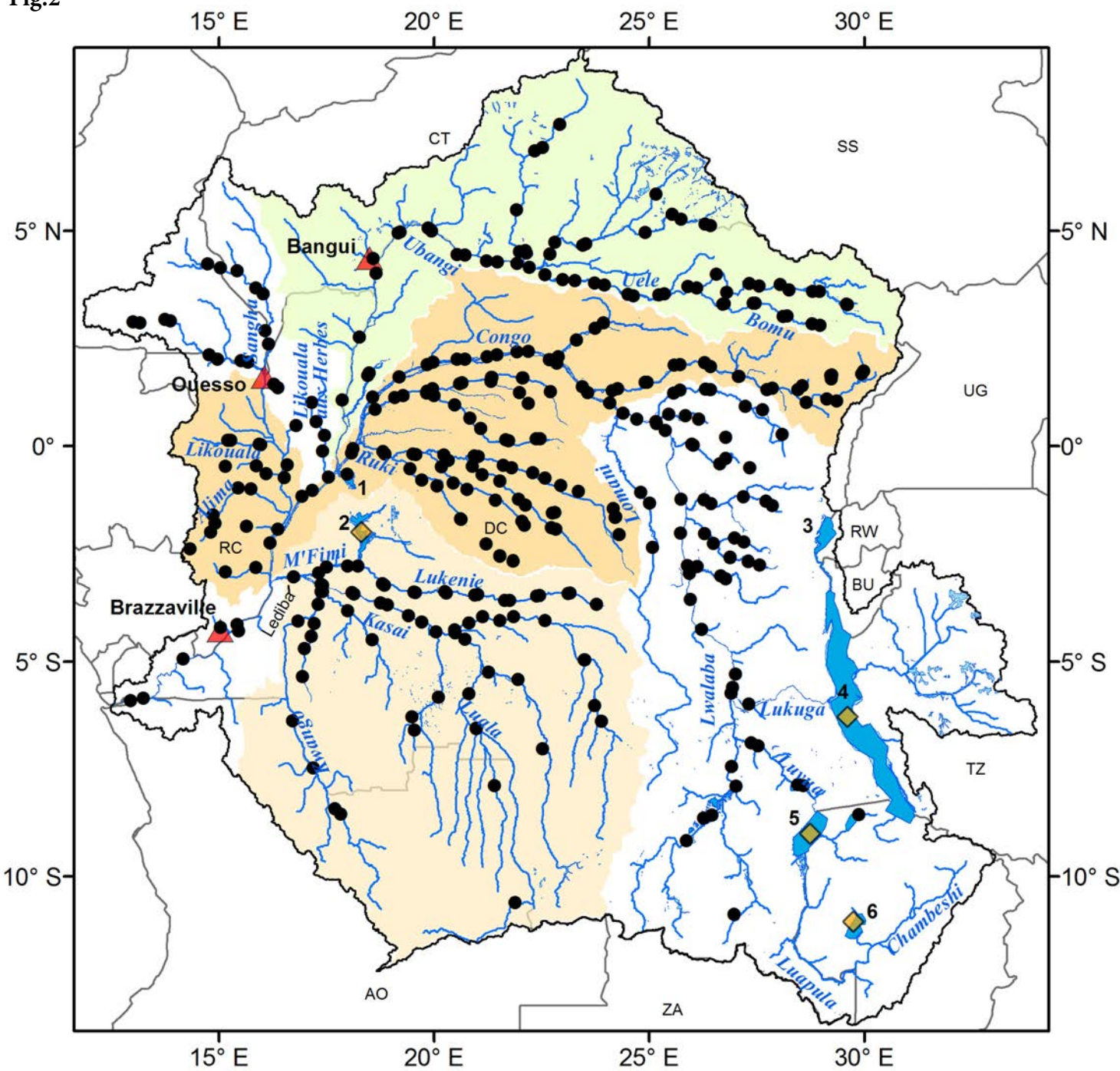




Fig.2



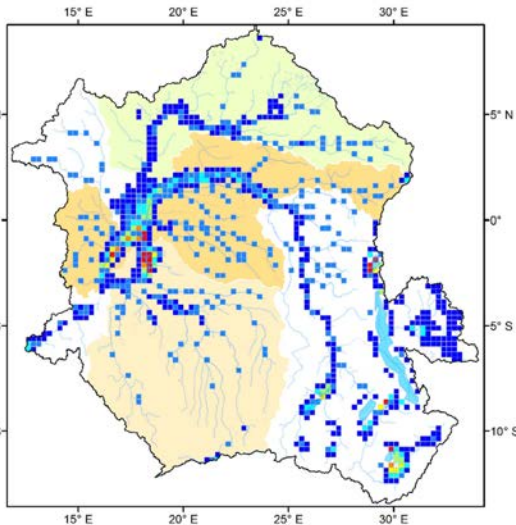


**Fig.3**

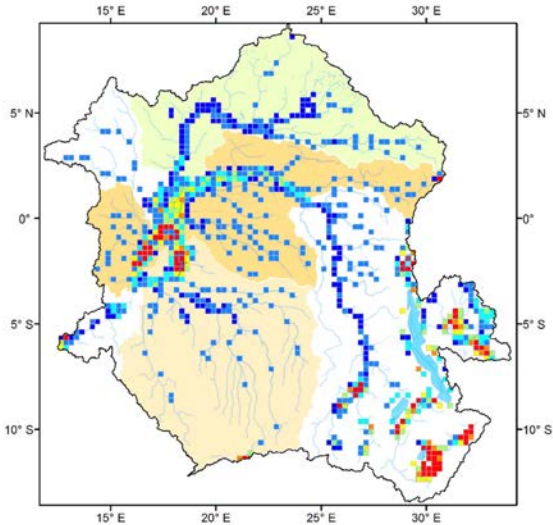
**Surface water extent over 1993-2007 (km<sup>2</sup>)**



**a. Mean**

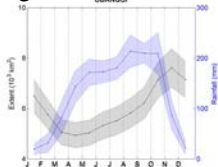


**b. Maximum**

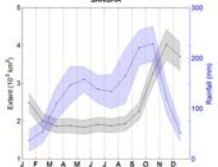


**Fig.4**

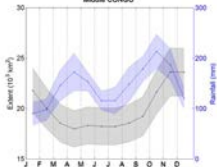
UBANGUI



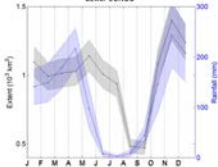
SANGHA



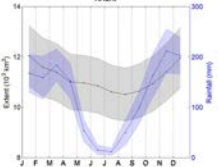
Middle CONGO



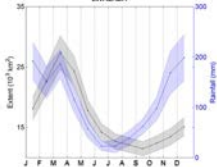
Lower CONGO

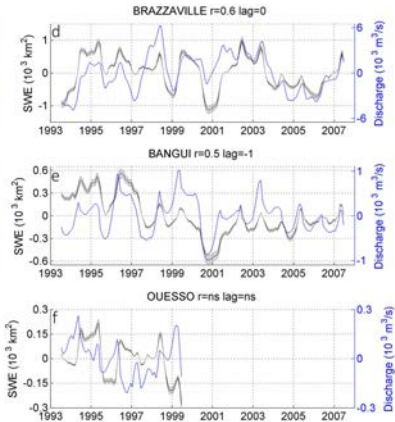
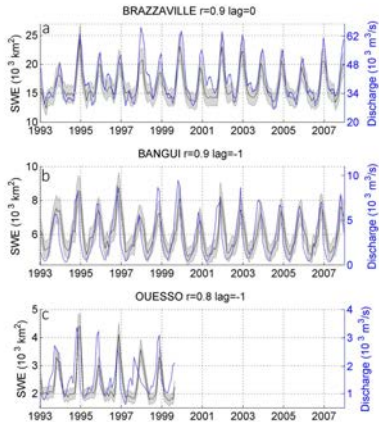


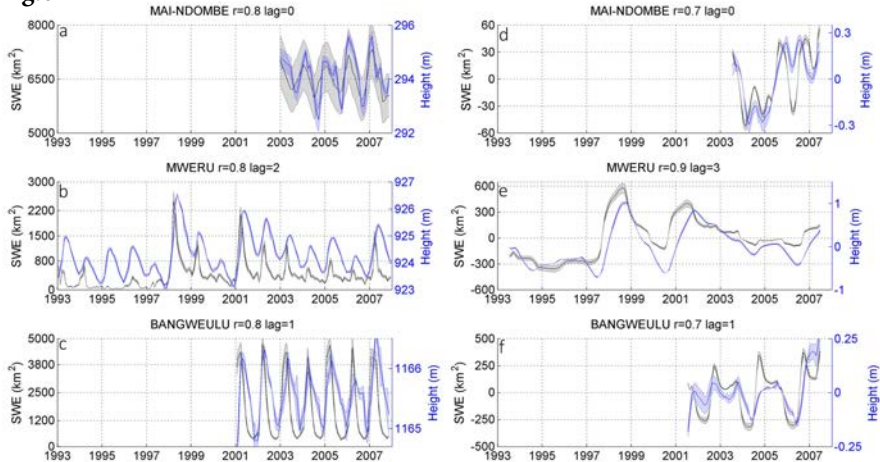
KASAI

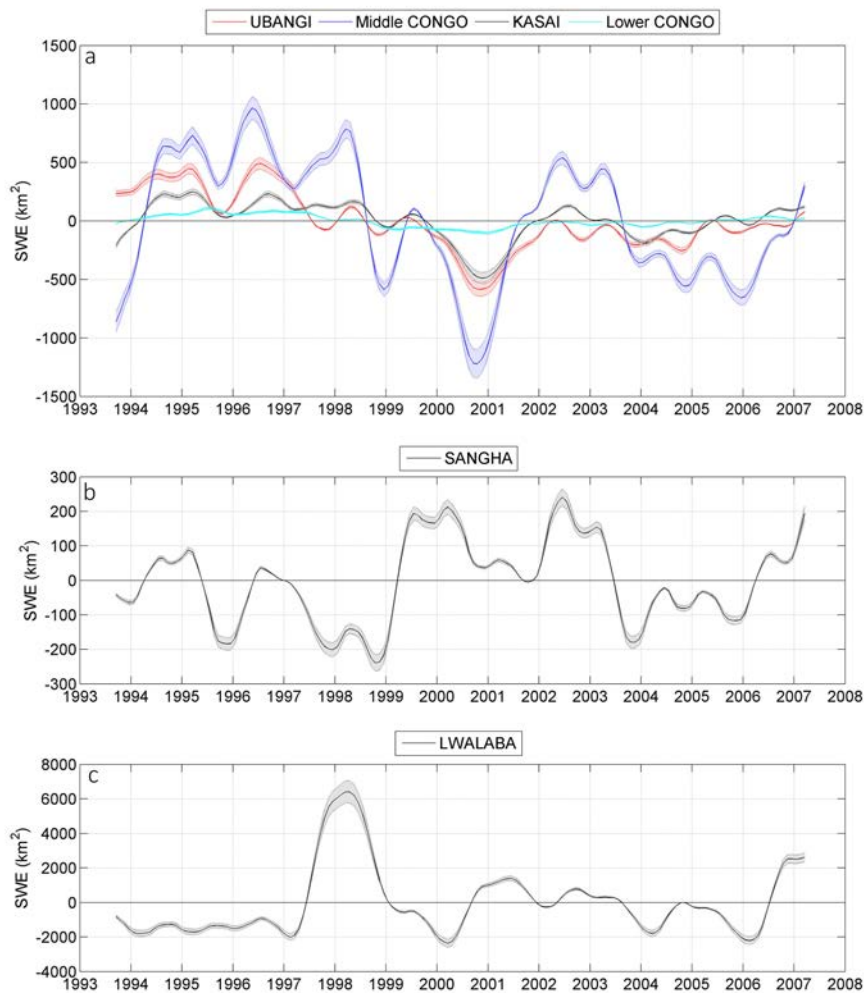


LWIALABA



**Fig.5**

**Fig.6**

**Fig.7**

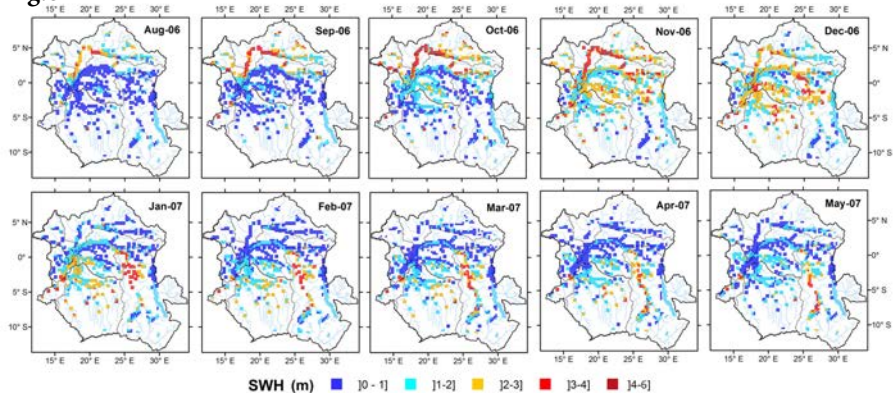
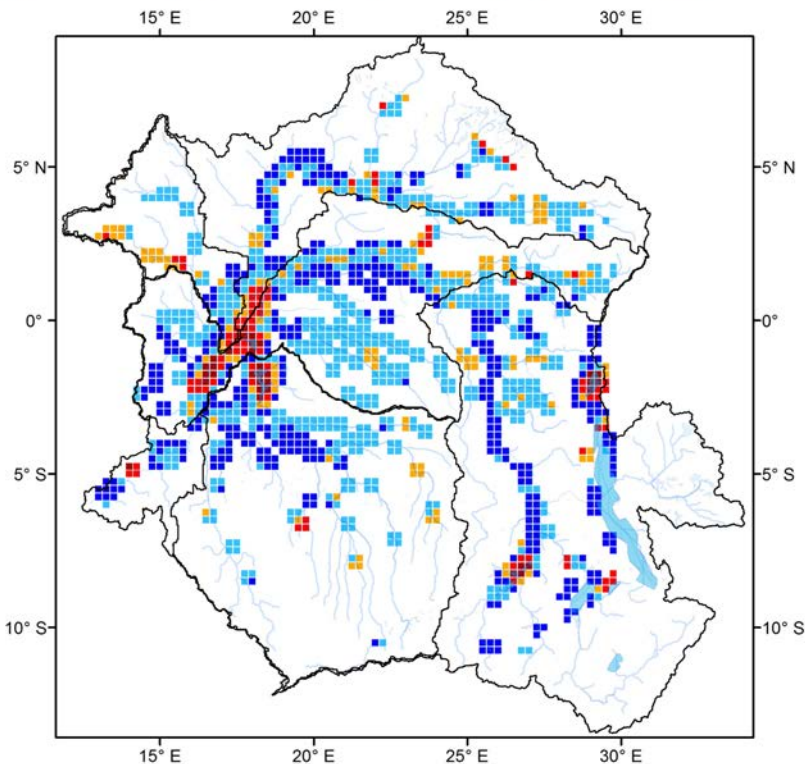
**Fig.8**

Fig.9

**Maximum annual amplitude of SWS over 2003-2007 (km<sup>3</sup>)**

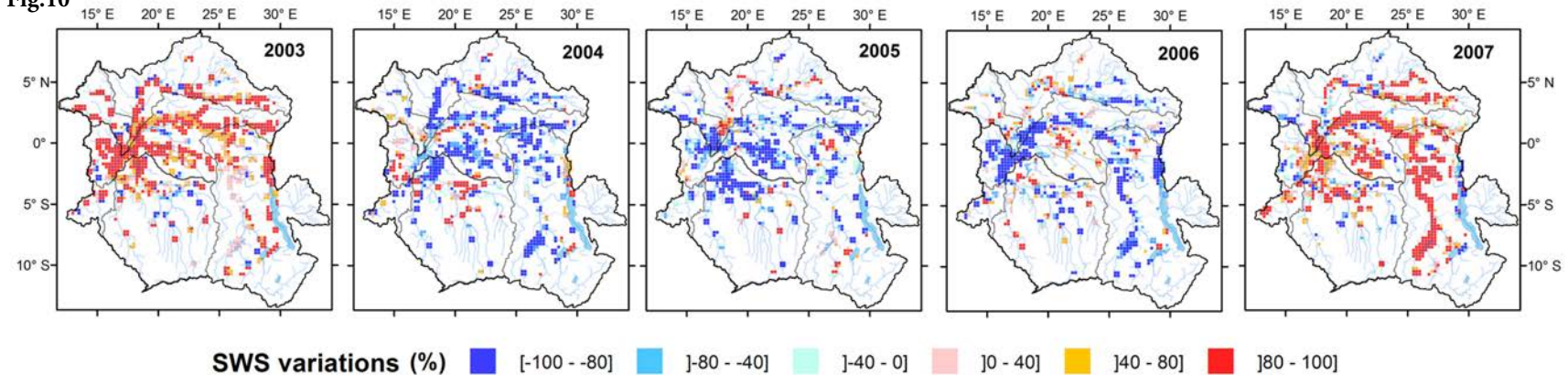
**Fig.10**



Fig.11

