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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

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

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

34

## 35 1. Introduction

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

55 18% of the world's tropical forests (~1100 10<sup>6</sup> ha, *Achard et al.*, 2002), and playing a  
56 crucial role as a sink of CO<sub>2</sub>, storing about 50 billion tons of carbon [*Verhegghen et al.*,  
57 2012]. In a recent study, *Dargie et al.*, [2017] highlighted that the “Cuvette Centrale”  
58 peatland (Fig.1) stores about 30 billion tons of carbon. This total amount of carbon is  
59 equivalent to ~ 80 billion tons of CO<sub>2</sub> or about 2.3 years of current global anthropogenic  
60 emissions (~ 35 billion tons in 2015, *Olivier et al.*, 2016). This stock is particularly  
61 vulnerable to land-use change and any future change in the water cycle. For all these  
62 reasons, there is an obvious need to better understand the CRB dynamic and to characterize  
63 its vulnerability to climate change and other crucial challenges. In particular, it is necessary  
64 to gain solid knowledge about the past and current hydro-climate processes of the CRB, in  
65 order to significantly reduce the uncertainties associated with future climate response  
66 under global warming. The limited understanding of the CRB's hydro-climate processes  
67 results mainly from the lack of *in situ* data availability: the network of stations, which data  
68 are publicly released, is sparse and poorly maintained, and it is substantially difficult of  
69 perform fieldwork, notably in the swamps. However, recent developments and  
70 improvements in remote sensing technology provide more observations than ever before  
71 [*Alsdorf et al.*, 2007; *Prigent et al.*, 2016] and allow us the unique opportunity to better  
72 understand the spatial and temporal variability of the CRB's hydro-climatic patterns.

73

74 In this study, our primary focus is on the CRB surface water (SW) dynamics, a key  
75 component of the land water budget equation. The SW, corresponding to water stored in  
76 rivers, lakes, wetlands, floodplains and in man-made reservoirs, is crucial to the survival of  
77 all living organisms, including humans and is a precious resource in term of biodiversity,  
78 ecology, water management and economy. Moreover, SW storage (SWS) plays a major  
79 role at all scales in the terrestrial water balance and in the Earth's climate system  
80 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>.

107 *Crowley et al.*, [2006], using Gravity Recovery and Climate Experiment (GRACE) data,  
108 estimated the terrestrial water storage (surface water storage plus groundwater storage and  
109 soil moisture) within the CRB. Over 4 years (2002-2006), the estimate exhibited  
110 significant seasonal variations ( $30\pm 6$  mm of equivalent water thickness) and long-term  
111 negative trend ( $\sim -70\text{km}^3/\text{year}$ ). *Lee et al.*, [2011], using GRACE data and other satellite  
112 measurements, estimated that the amount of water annually filling and draining the Congo  
113 wetlands is about  $111\text{ km}^3$ , i.e. one-third the magnitude of the water volumes found on the  
114 mainstream Amazon floodplain. *Lee et al.*, [2014], integrating terrestrial water storage  
115 (TWS) changes from GRACE, water level changes from radar altimetry, and inundation  
116 extents from SAR imagery, quantified TWS change and its surface and subsurface  
117 components over the central CRB. They showed that annual variations of the TWS  
118 changes during the period of 2007–2010 from  $21$  to  $31\text{ km}^3$  and are mostly controlled by  
119 surface storage changes. *Lee et al.*, [2015] developed water depth maps over the “Cuvette  
120 Centrale” based on a linear regression model from altimetry and imagery data. They  
121 reported in their study area water storage volumes of about  $11\text{ km}^3$  (Dec-2006),  $10\text{ km}^3$   
122 (Dec-2007), and  $9\text{ km}^3$  (Dec-2008). Finally, *Becker et al.*, [2014] released an  
123 unprecedented dataset of water level time series over the entire CRB for the period 2003 to  
124 2009, obtained from the ENVISAT radar altimetry mission. From this unique data set, they  
125 proposed an altimeter-based river level height regionalization scheme and thus identified  
126 nine distinct hydrological regions in the CRB.

127

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

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

143

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

145 The CRB is a transboundary basin located in equatorial Africa (Fig. 1). In the heart of the  
146 CRB, the shallow depression along the equator is named the “Cuvette Centrale” [Bernard,  
147 1945] (Fig. 1). The Congo River begins its course at the Chambeshi River (Fig. 2), rising  
148 south of the Lake Tanganyika and transferred by the Bangweulu Swamps. After flowing  
149 through Lake Mweru, it joins the Lwalaba River [Balek, 1977]. The permanent surface  
150 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  
151 of the rainy season when its swamps and floodplains get flooded. Lake Mweru covers  
152 about 4,650 km<sup>2</sup>, and is surrounded by permanent swamps (~1,500 km<sup>2</sup>) and floodplains  
153 (~900 km<sup>2</sup>). The Kasai River from the south, and the Ubangi River from the north are the  
154 two principal tributaries of the Congo River. Right-bank tributaries of the Congo River  
155 below its junction with the Ubangi include the Likouala aux Herbes, Sangha, Likouala and  
156 Alima rivers. Swamp forests predominate on the floodplains in this section [Beadle, 1981;  
157 Hughes *et al.*, 1992; Betbeder *et al.*, 2014]. The coupled ocean-atmosphere modes of El  
158 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.

### 171 **3. Dataset**

#### 172 **3.1. ENVISAT radar altimeter observations**

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

193

#### 194 **3.2. GIEMS surface water extent dynamics**

195 A globally applicable remote-sensing technique has been developed to derive wetland  
196 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 km<sup>2</sup>). 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

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

225

### 226 **3.3. Ancillary data**

#### 227 **3.3.1. GRACE Regional Solution**

228 The Gravity Recovery And Climate Experiment (GRACE) mission, placed in orbit in  
229 March 2002, provides data over the continents and can be used to derive the monthly  
230 changes of the terrestrial water storage (TWS) expressed in terms of equivalent water  
231 height (EWH) [Tapley *et al.*, 2004]. In this work, we used maps of monthly TWS from the  
232 Jet Propulsion Laboratory GRACE land mascon solution (JPL RL05M, available at  
233 <http://grace.jpl.nasa.gov>). This solution proposed some improvements to reduce leakage  
234 errors i) across land/ocean boundaries using a Coastline Resolution Improvement filter and  
235 ii) for continental hydrology applications providing a set of gain factors. The description of  
236 the JPL RL05M solution in detail can be find in *Watkins et al.*, [2015] and *Wiese* [2015].  
237 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  
238 the CRB, the measurement error dominates the leakage error, i.e 5.3 mm vs 2.7 mm  
239 respectively of EWH [Wiese *et al.*, 2016]. Over land, the scaled uncertainty derived using  
240 methods described in *Wahr et al.*, [1998] are provided and are in the range [0.7 15.8] mm  
241 of EWH over the CRB.

242

#### 243 **3.3.2. Rainfall datasets**

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

245 We used the Climatic Research Unit (CRU) Time-series (TS) version 4.00 (CRU TS4.00)  
246 [Harris *et al.*, 2014; Harris and Jones, 2017]. These data are rainfall gridded fields based  
247 on monthly observations at meteorological stations across the world's land areas and are  
248 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)

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

276

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

278 The mean and maximum of the SWE per grid cell over 1993 to 2007 are displayed in Figs.  
279 3a and 3b. A very realistic spatial distribution of the major rivers (Congo, Kasai, Ubangi  
280 and Lwalaba) and some tributaries is shown by these maps. Associated inundated areas,  
281 wetlands and the region of the “Cuvette Centrale” are also well delineated. Maxima are  
282 located in two regions: (i) in the Lwalaba basin, mainly along the major lakes; and (ii) in  
283 the “Cuvette Centrale” along the Congo main stream, between 15°-18°E and 0°-2.5°S,  
284 including Lake Mai-Ndombe and Lake Tumba. The SWE and precipitation seasonal  
285 variations are presented in Fig. 4 and in Table 1. In this analysis, we computed the monthly  
286 rainfall averages over 1993-2007 from CRU TS4.00, GPCP and TRMM products. In  
287 Ubangi, Sangha and Middle Congo sub-basins, the precipitation dynamics present a  
288 bimodal distribution, which is not observed in the SWE seasonal variations. However,  
289 SWE in Ubangi and Middle Congo follow slowly the overall increase trend of precipitation  
290 from April to November. The SWE in Sangha presents a sharp increase from September to  
291 November. The SWE in these three sub-basins drops a month after the beginning of the  
292 precipitation decrease and reaches their minima 2-3 months after those of precipitation.  
293 These three sub-basins see their flooded area increase two to three-fold on average over the  
294 year. For instance, in the Middle Congo, the flooded areas vary from 16,700 km<sup>2</sup> at low  
295 waters to 26,000 km<sup>2</sup> at high waters. The SWE in Kasai shows very little variations over  
296 the year, probably due to the low GIEMS data coverage in this specific area. In the Lower  
297 Congo, between August and December, the SWE drops a month after the beginning of the  
298 precipitation decrease and reach its minimum 3 months after the precipitation minimum.

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

301

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

312

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

322

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

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

338

339 In order to better characterize SWE interannual variability and its possible relation with  
340 large climate events, we further analyze the deseasonalized anomalies between 1993 and  
341 2007 (Fig. 7). The SWE interannual variability over the Ubangi, Kasai, Middle Congo and  
342 Lower Congo show the same dynamics (Fig 7a). A large negative anomaly in SWE is  
343 observed from 1998 to 2000, which could be associated with the 1998-2000 persistent La  
344 Niña event. This type of event is often linked to drier than normal conditions over  
345 equatorial East Africa [McPhaden, 2002]. The SWE interannual variability over the  
346 Lwalaba basin (Fig. 7c) presents a large positive event in 1997/1998, previously observed  
347 in the Mweru Lake height variations (Fig. 6b/e), where a pIOD event (associated with an  
348 excess of rain in western Indian Ocean, South India, and East Africa) occurs in conjunction  
349 with an El Niño event [Ummenhofer *et al.*, 2009]. For example, after the 1997 pIOD event,  
350 the level of Lake Victoria rose by 1.7 m, Lake Tanganyika by 2.1 m and Lake Malawi by



351 1.8 m; the Sudd marshes levels also rose [Birkett et al., 1999; Becker et al., 2010] and very  
352 high river flows were measured at Kinshasa [Conway et al., 2005]. Moreover, these  
353 devastating floods have resulted in several thousand deaths and hundreds of thousands  
354 people have been displaced in Kenya, Somalia, Sudan, Uganda, and Ethiopia [Cai et al.,  
355 2014]. In the Lwalaba basin, the SWE increased significantly by a factor of ~4 from late  
356 1997 to the end of 1998.

357

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

359 Here we present the spatio-temporal variability of SWS estimated by combining the SWE  
360 from GIEMS with the 350 altimeter-derived water level heights. The two-step  
361 methodology is described briefly in the following sections and we refer to Frappart et al.,  
362 [2008, 2011] for more details. The results are analyzed for 2003-2007, the common period  
363 of availability for both datasets.

### 364 **5.1. Monthly maps of surface water level anomalies**

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

$$372 \quad h_{min}(\lambda_j, \varphi_j, \alpha, \Delta T) = \min \left( h(\lambda_j, \varphi_j, t) \right)_{P(\lambda_j, \varphi_j, t) \leq \alpha; t \in \Delta T} \quad (1)$$

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

376 Fig. 8 shows the seasonal evolution of surface water heights (SWH) in the CRB sub-basins  
 377 for the period August 2006 to May 2007 covering a pIOD-El Niño event. In the Ubangi  
 378 and Sangha basins the SWH increase in August-October (up to 4 m) and reach their  
 379 maximum values in November (up to 6 meters). In the Middle Congo River Basin, SWH  
 380 increase from October to December and show an important spatial variability. The SWH  
 381 highest values (~3 m) are along the Congo River mainstream and in the south of the basin  
 382 along the Ruki River. From January, we observe increases in the southern part of the CRB  
 383 basin. In the upper Lwalaba basin we observe from January to March an important  
 384 inundation zone (up to 4 m). From April, the SWH start to decline. The monthly maps of  
 385 SWH are now used to estimate surface water storage expressed as volumes for 2003–2007.  
 386

### 387 **5.2. Monthly time series of surface water volume variations**

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

$$390 \quad V_{SW}(t) = R_e^2 \sum_{j \in S} P(\lambda_j, \varphi_j, t) \left( h(\lambda_j, \varphi_j, t) - h_{min}(\lambda_j, \varphi_j) \right) \cos(\varphi_j) \Delta\lambda \Delta\varphi \quad (2)$$

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

396

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

$$399 \quad \Delta V_{SW}(t) = S(t-1) |\Delta h(t)| + \text{sgn}(\Delta h(t)) \frac{|\Delta S(t)| |\Delta h(t)|}{2} \quad (3)$$

400 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  
 401 of the lake between instants  $t$  and  $t-1$  respectively.

402

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

406

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

$$410 \quad \Delta V_{TWS}(t) = R_e^2 \sum_{j \in S} \Delta h_{TWS}(\lambda_j, \varphi_j, t) \cos(\varphi_j) \Delta \lambda \Delta \varphi \quad (4)$$

411 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  
 412 coordinates  $(\lambda_j, \varphi_j)$ ,  $R_e$  the earth's radius (6378 km),  $\Delta \lambda$  and  $\Delta \varphi$  are respectively the grid  
 413 steps in longitude and latitude. The maximum error for the SW volume variation (km<sup>3</sup>),  
 414  $\Delta V$ , is estimated as :

$$415 \quad \max(\Delta V) = S_{max} \Delta \delta h_{max} + \Delta S_{max} \delta h_{max} \quad (5)$$

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

420

421 Fig. 9 presents the spatial patterns of SWS changes, estimated as the year among the five  
 422 years being the maximum range of SWS. It shows realistic spatial structures along the  
 423 Congo River and the ‘‘Cuvette Centrale’’, as well as in the Tumba and Mai-Ndombe lakes,  
 424 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  $28 \pm 4$

451 km<sup>3</sup> for the Kasai. The Middle Congo presents a mean annual SWS amplitude of 43±7  
452 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  
453 contrast, the Lwalaba basin shows an annual SWS minimum of ~30 km<sup>3</sup> observed in 2007  
454 and a maximum of ~41 km<sup>3</sup> in 2005. On average this basin shows a mean annual SWS  
455 amplitude of 34±4 km<sup>3</sup>, where we have included the volume variations of Bangweulu,  
456 Mweru and Tanganyika Lakes obtained from the combination of altimetry and GIEMS.  
457 We estimated the maximum error for the SWS change in the CRB using Equation (5) and  
458 using the following values:  $S_{max} = 78\,932\text{ km}^2$  in February, 2007;  $\delta h_{max} = 0.6\text{ m}$ , mean  
459 maximum SWH change between two consecutive months during 2003-2007;  $\Delta S_{max} = 10\%$   
460 from *Prigent et al.*, [2007] of  $78\,932\text{ km}^2$ ; and  $\Delta\delta h_{max} = 0.2\text{ m}$ , maximum average  
461 dispersion of the SWH in 2007. We obtain a maximum error of ~20 km<sup>3</sup> for an annual  
462 variation of 76 km<sup>3</sup> in 2007, i.e., an error of ~26%. This value is of the same order of  
463 magnitude as that obtained over the Rio Negro (~23% *Frappart et al.*, [2008]), over the  
464 Orinoco Basin (~30%, *Frappart et al.*, [2015b]) and over the Ganges-Brahmaputra Basin  
465 (~24%, *Papa et al.*, [2015]). In the same way, we obtained over the sub-basins the  
466 maximum errors of ~17% for the Ubangui, ~23% for the Sangha, ~17% for the Middle  
467 Congo, ~19% over the Kasai, and ~27% over the Lwalaba. Respectively, the mean annual  
468 variation in SWS represents 13±2 % of the total volume of water that flows out the Ubangi  
469 basin and at the Sangha mouth, 8±1 % at the Kasai mouth, 9±1 % along the Congo River  
470 above the Ubangi mouth and ~13±2% at the Lwalaba mouth.

471

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

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

482

483 We subtract SWS to TWS in order to obtain the “sub-surface water storage” variations  
484 (Sub-SWS, Fig.11) defined as the sum of soil moisture and groundwater. We assume that  
485 the variations in water storage compartments derived from canopy are negligible over the  
486 2003-2007 in the CRB and hence are not considered here. The Sub-SWS contribution  
487 (Fig.11) in the Ubangi, Sangha and Lwalaba basins is very important and suggests that the  
488 hydrological compartments, such as soil moisture and groundwater, have a major influence  
489 on TWS. On the contrary, in the Middle Congo, the SWS alone contributes over one-third  
490 of the TWS variations over this sub-basin.

491

## 492 **6. Conclusions and perspectives**

493 This work presents an unparalleled analysis of the dynamics of surface water extent (1993–  
494 2007) and storage (2003-2007) in the CRB. First, we show that the SWE seasonal patterns  
495 from GIEMS dataset exhibit very realistic distributions of major rivers (Congo, Kasai,  
496 Ubangi and Lwalaba) and their tributaries, with two maxima located: i) in the lake region  
497 of the Lwalaba sub-basin and ii) in the “Cuvette Centrale”, including Tumba and Mai-  
498 Ndombe Lakes. For the period 1993-2007, we found a ENSO/IOD influence on the SWE  
499 interannual variability. Following the approach developed by Frappart *et al.* [2008, 2011],  
500 we combined GIEMS observations with inland water level variations from ENVISAT  
501 radar altimetry (350 observations on the rivers) to analyze the variations of fresh water  
502 stored in the CRB different hydrological compartments. Overall, during 2003-2007, the

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

527

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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 périallantiques : 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. Pocard (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/edf8febfdaad48abb2cbaf7d7e846a86.
- 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. Sigha-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 Ouesso) 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 Ouesso 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**

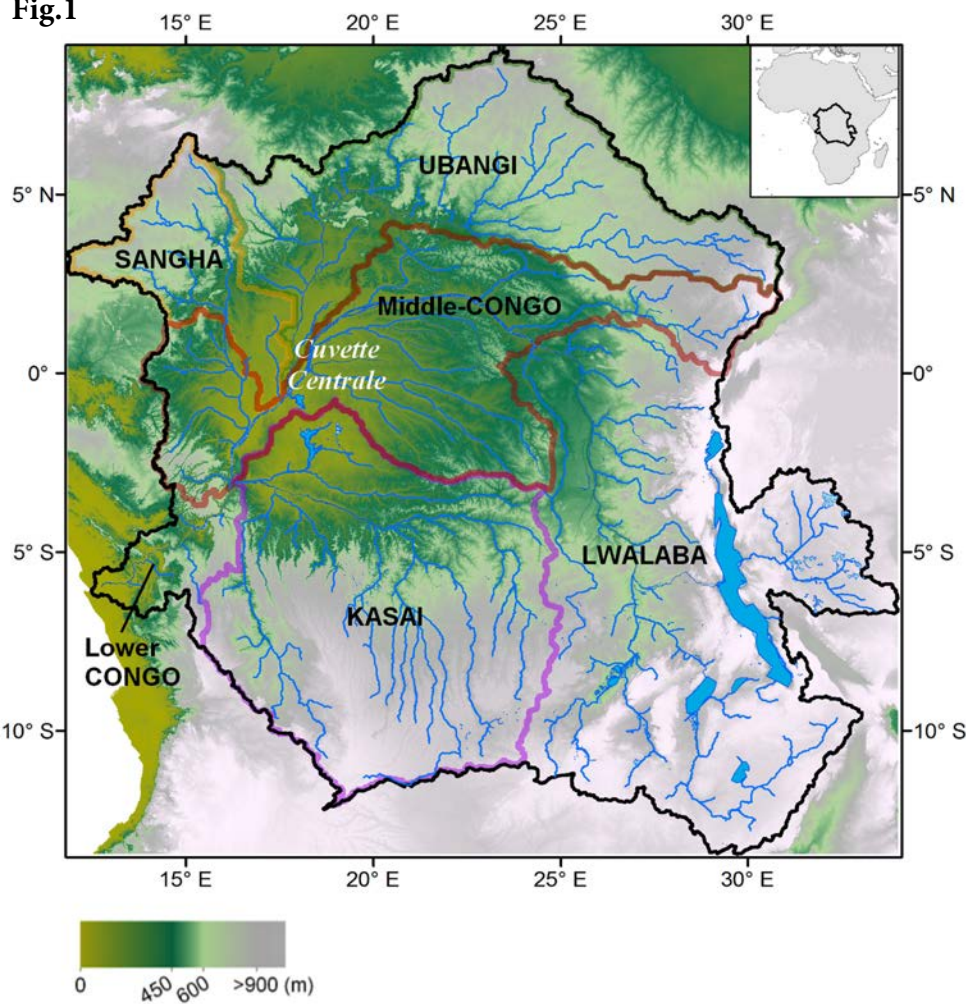
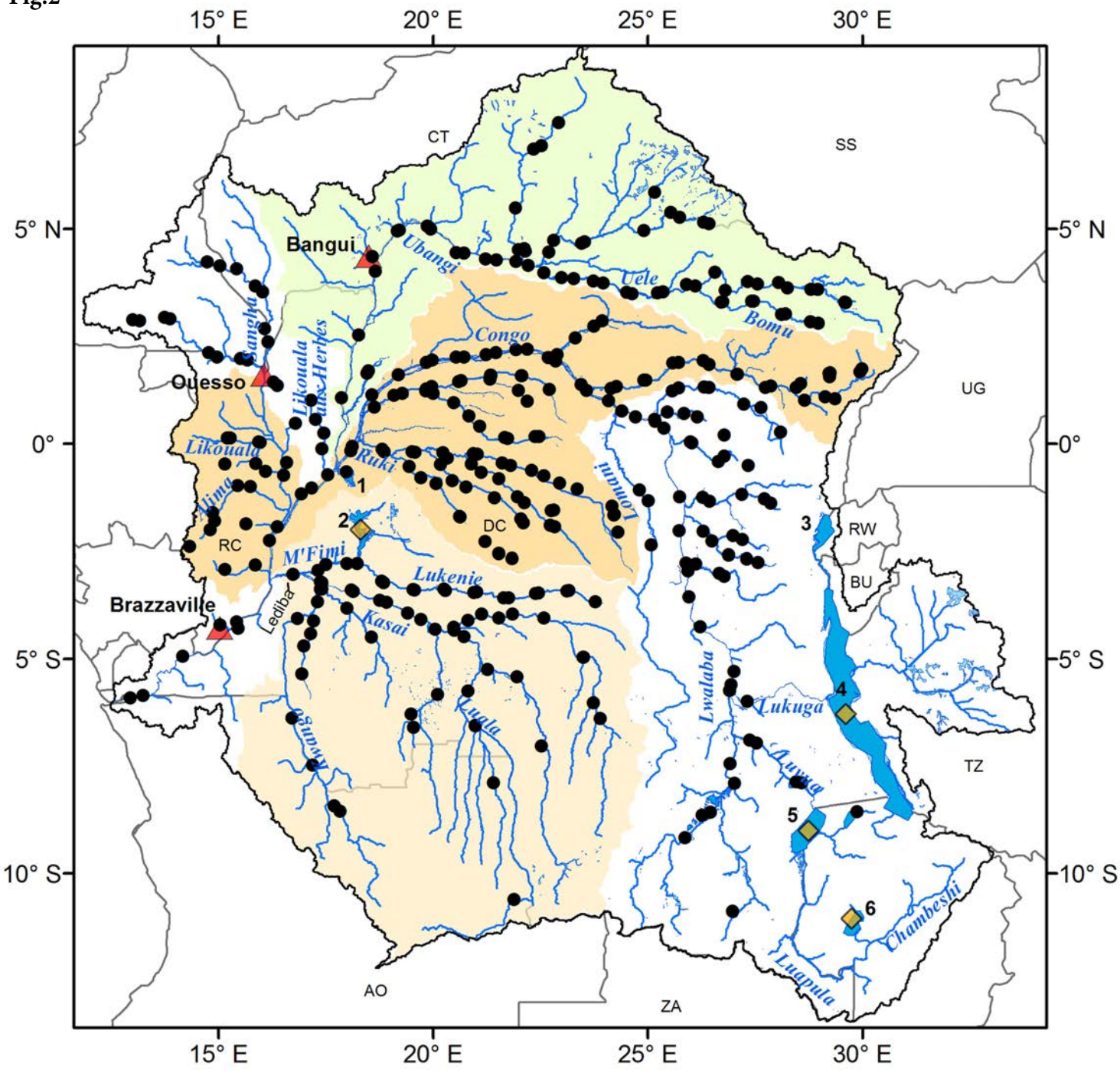
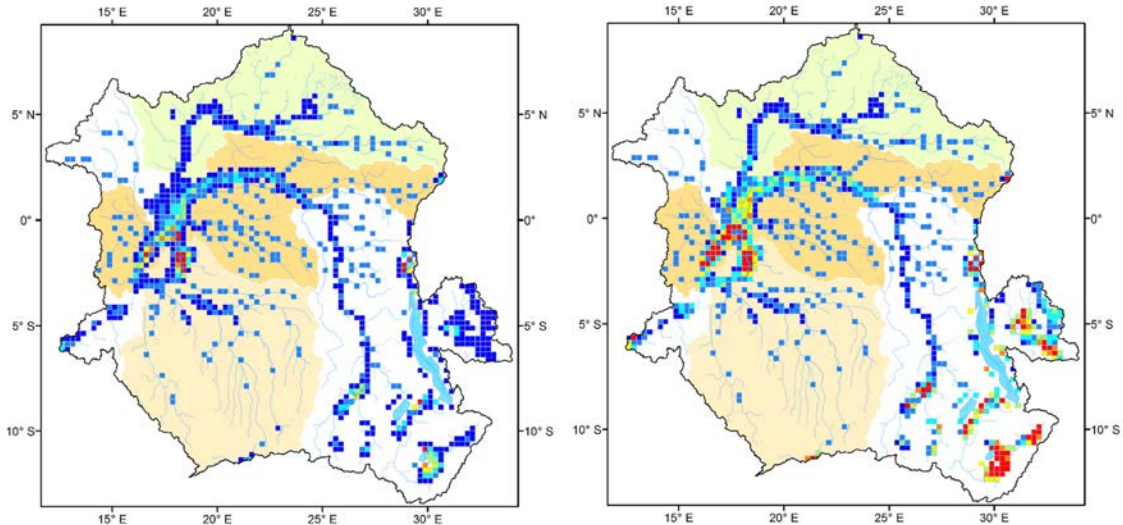
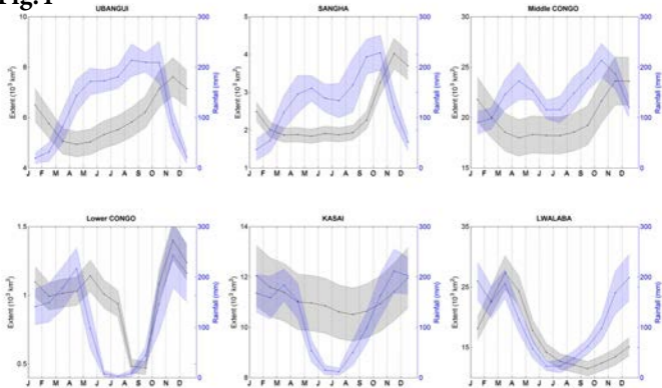


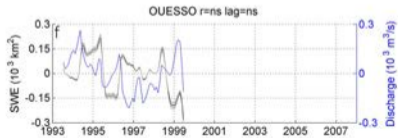
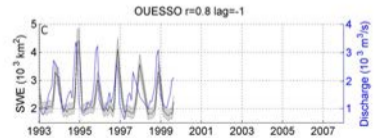
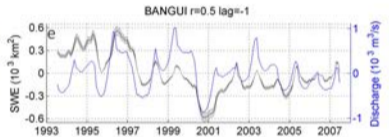
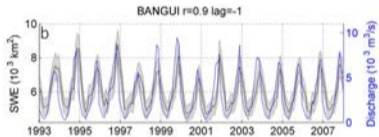
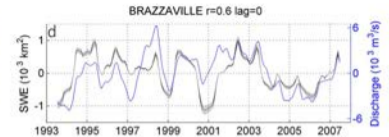
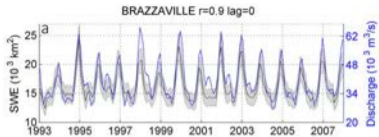
Fig.2

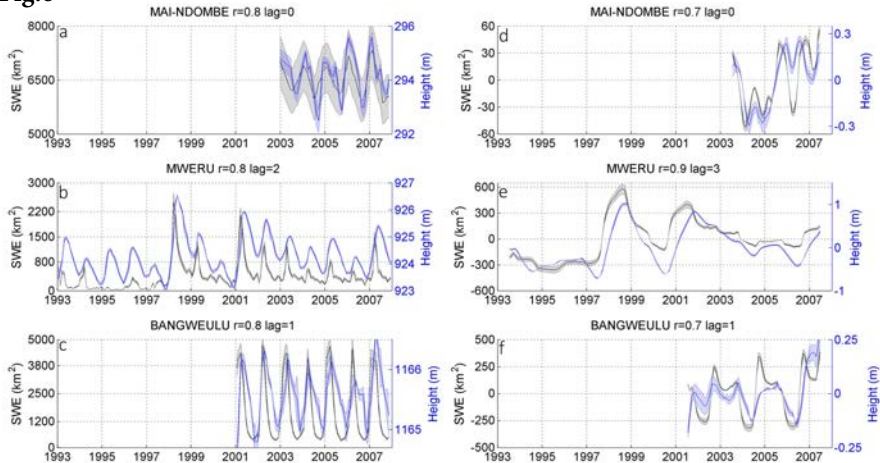


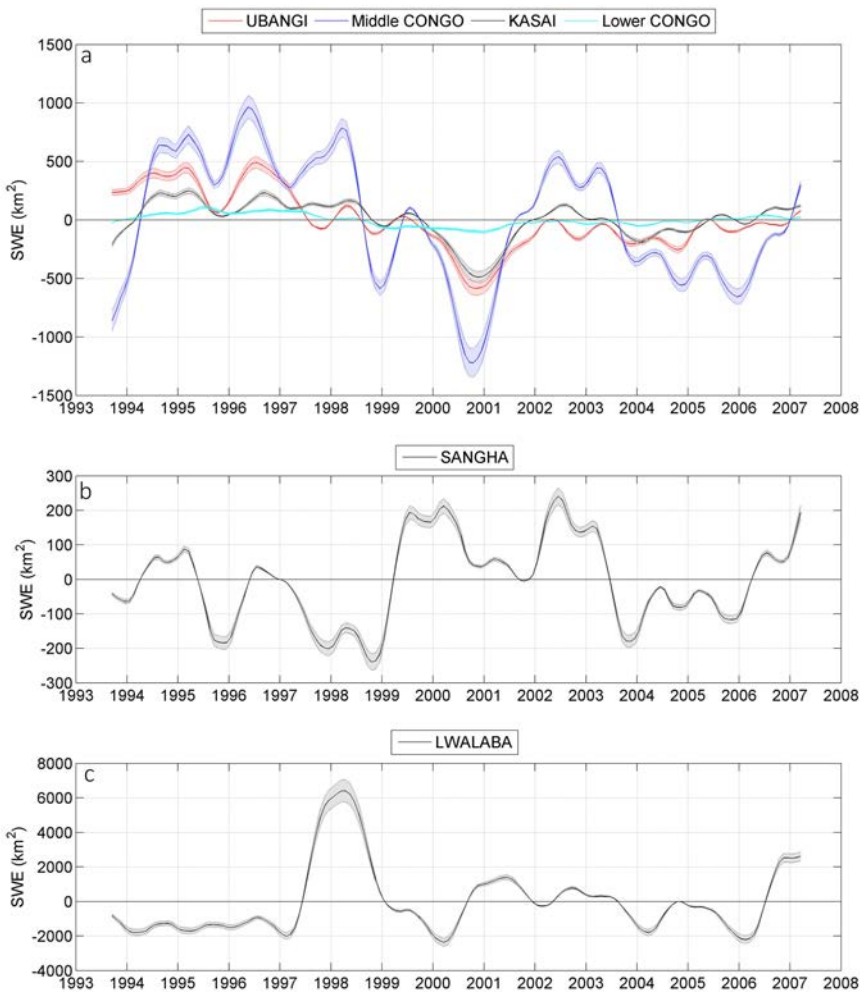


**Fig.3****Surface water extent over 1993-2007 (km<sup>2</sup>)****a. Mean****b. Maximum**

**Fig.4**

**Fig.5**

**Fig.6**

**Fig.7**

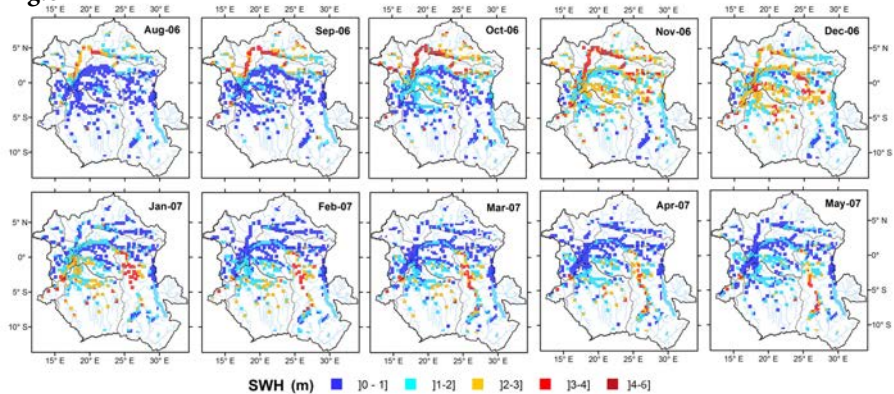
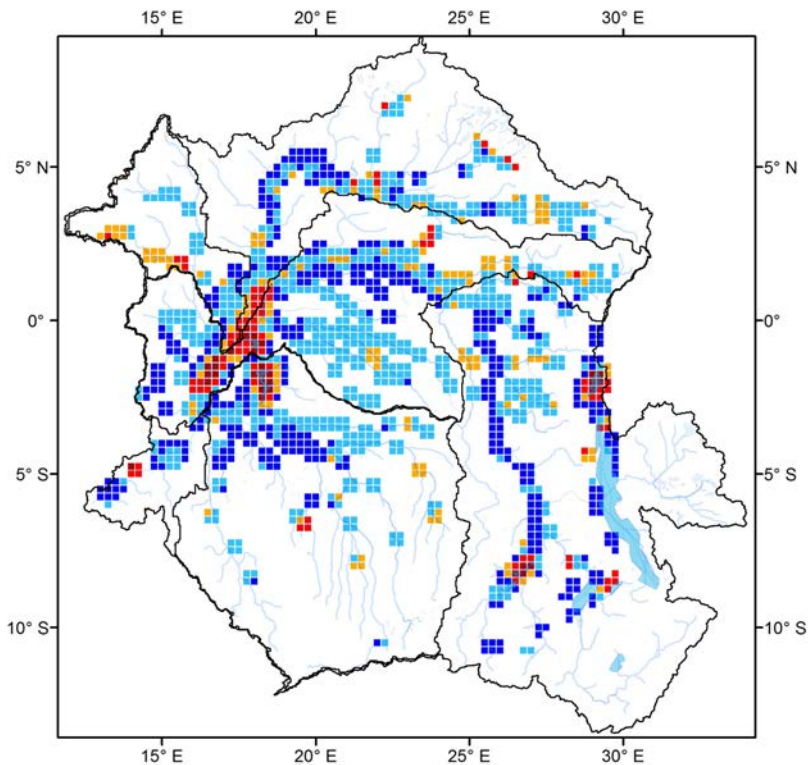
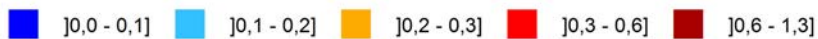
**Fig.8**

Fig.9

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

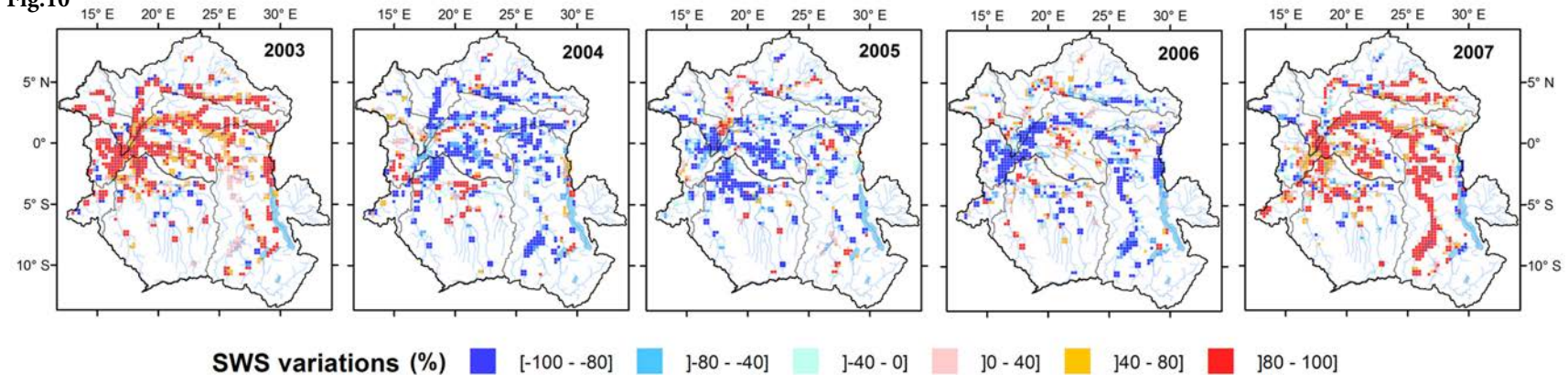
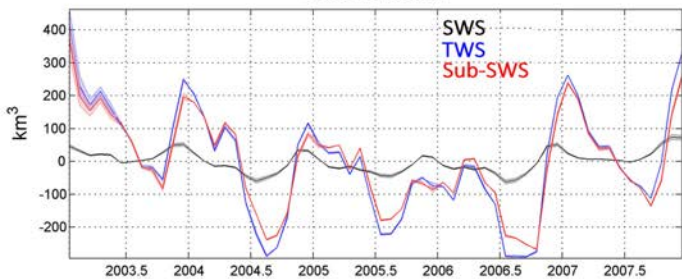
**Fig.10**

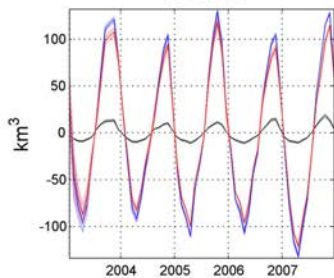


Fig.11

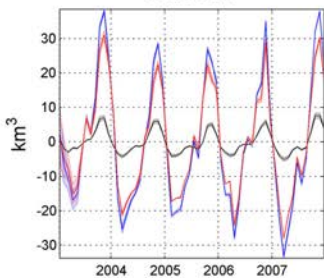
CONGO BASIN



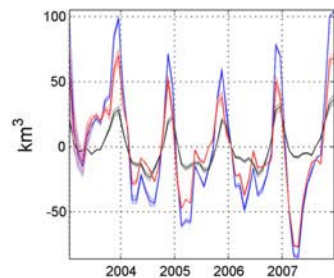
UBANGI



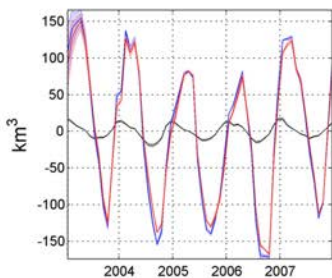
SANGHA



Middle CONGO



KASAI



LWALABA

