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

M. Becker^{1,*}, F. Papa^{2,3}, F. Frappart^{2,4}, D. Alsdorf⁵, S. Calmant², J. Santos da Silva⁶, C.
Prigent⁷ and F. Seyler⁸

¹ LIENSs/CNRS, UMR 7266, ULR/CNRS, 2 rue Olympe de Gouges, La Rochelle, France

² LEGOS/IRD, UMR 5566, CNES/CNRS/IRD/UPS, 14 Avenue Edouard Belin, Toulouse, France

³ Indo-French Cell for Water Sciences, IRD-IISc-NIO-IITM, Indian Institute of Science, Bangalore, India

⁴ GET/GRGS, UMR 5563, CNRS/IRD/UPS, OMP, 14 Avenue Edouard Belin, Toulouse, France

⁵ Byrd Polar and Climate Research Center and School of Earth Sciences, Ohio State University, OH, USA.

⁶ UEA/CESTU, Av. Djalma Batista 3578, Manaus, Brazil

⁷ CNRS, LERMA, Observatoire de Paris, Paris, France

⁸ ESPACE-DEV/IRD, UMR 228, IRD/UM/UG/UR, MTD 500 rue J-F Breton, Montpellier, France

* *Corresponding author: melanie.becker@univ-lr.fr.*

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 ± 24 km³ and contributes to 19 ± 5 % of the annual
30 variations of GRACE-derived terrestrial water storage (33 ± 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 $\sim 40,600$ m³/s, and drainage
43 basin size ($\sim 3.7 \times 10^6$ km²) [*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 ($\sim 190 \cdot 10^6$ ha, *Verhegghen et al.*, 2012), representing about

55 18% of the world's tropical forests (~1100 10⁶ ha, *Achard et al.*, 2002), and playing a
56 crucial role as a sink of CO₂, 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 CO₂ 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 km².

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 ± 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 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 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 km^3 (Dec-2006), 10 km^3
122 (Dec-2007), and 9 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 km² and can expand to about 15,000 km² at the end
151 of the rainy season when its swamps and floodplains get flooded. Lake Mweru covers
152 about 4,650 km², and is surrounded by permanent swamps (~1,500 km²) and floodplains
153 (~900 km²). 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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166
167

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

168
169
170

^a: The constant surface of the Tanganyika Lake, around 32,600 km², 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 μm) and near-infrared (0.73– 1.1 μm) 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^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

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 (0.5×0.5 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 km² at low
295 waters to 26,000 km² 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 km² and 1,900 km²) 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 (λ_j, φ_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 ΔT for a
374 percentage of inundation α from GIEMS, which varies between 0 and 100 and t is a
375 monthly observation during ΔT .

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 (km³) 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 (λ_j, φ_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 ΔV_{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 km² 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 (km³) at time t of the pixel of
 412 coordinates (λ_j, φ_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 (km³),
 414 ΔV , 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 (km²), δh_{max} is the maximum SWH variation
 417 (km) between two consecutive months, ΔS_{max} is the maximum error for the flooded surface
 418 (km²) 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 km³/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 km³/year per grid cell. Low SWS changes are observed in other locations of CRB (below
428 0.2 km³/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 ± 24 km³
442 (Fig. 11 and Table 1). A significant year-to-year variation is observed, with for instance an
443 annual amplitude of ~ 57 km³ in 2003 whereas the amplitude reaches 114 km³ in 2006.
444 That corresponds to 6 ± 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 $\sim 40,600$ m³/s (i.e.
446 $\sim 1,280$ km³/year). As a comparison, the Amazon River SWS annual variation corresponds
447 to ~ 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 ± 4 km³, with a minimum of ~ 20 km³ observed in 2004 and a maximum of ~ 30 km³ in
450 2007. We report an annual mean SWS amplitude of 10 ± 2 km³ for the Sangha and 28 ± 4

451 km³ for the Kasai. The Middle Congo presents a mean annual SWS amplitude of 43±7
452 km³, with a minimum of ~34 km³ observed in 2003 and a maximum of ~52 km³ in 2007. In
453 contrast, the Lwalaba basin shows an annual SWS minimum of ~30 km³ observed in 2007
454 and a maximum of ~41 km³ in 2005. On average this basin shows a mean annual SWS
455 amplitude of 34±4 km³, 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 km³ for an annual
462 variation of 76 km³ 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 ± 2 % in the Lwalaba sub-basins. For the
478 entire CRB, the seasonal SWS variations represent 19 ± 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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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 km² 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 km³ 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

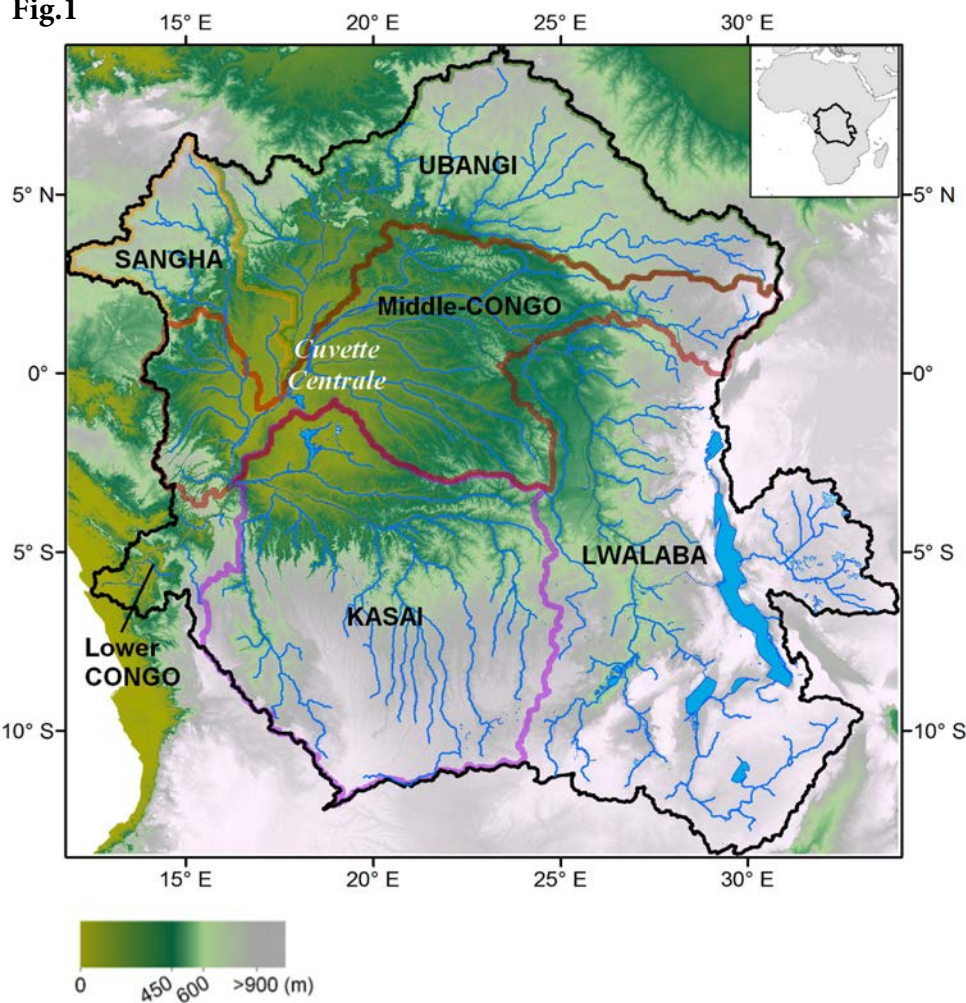


Fig.2

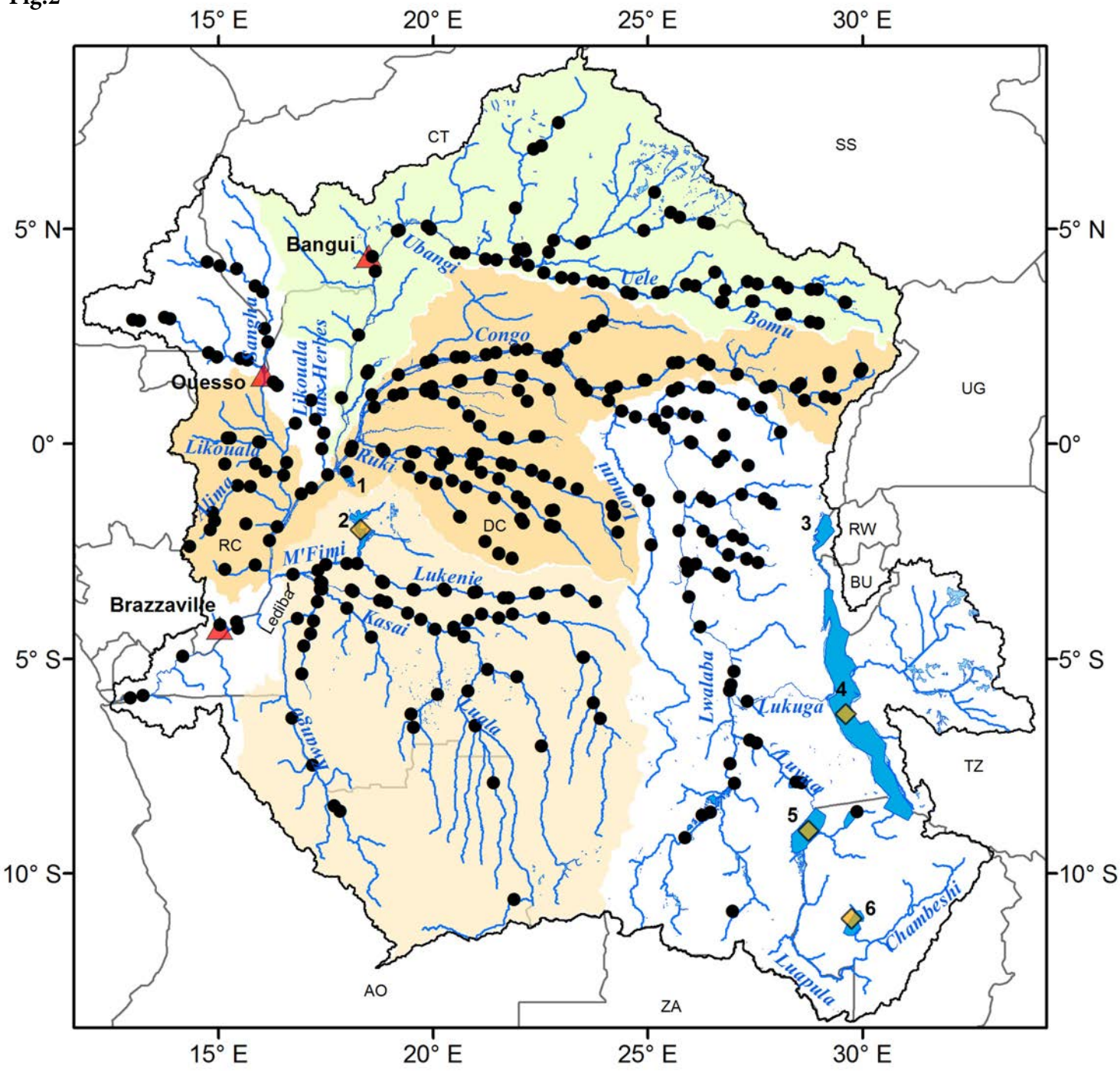


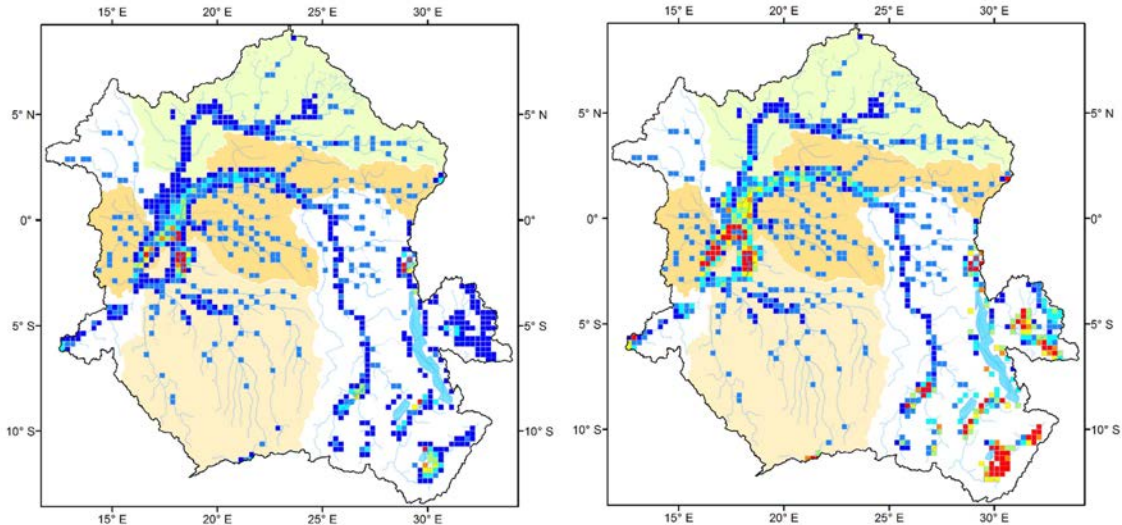
Fig.3**Surface water extent over 1993-2007 (km²)****a. Mean****b. Maximum**

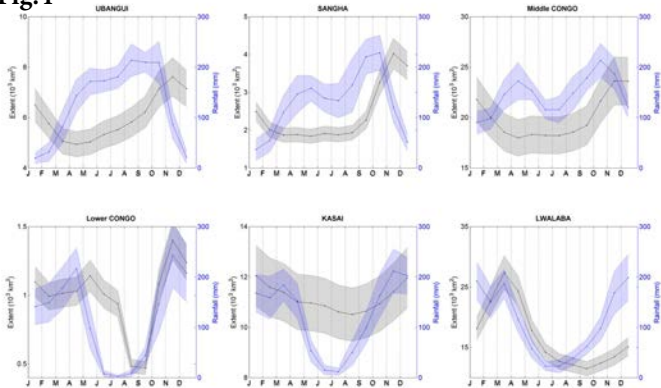
Fig.4

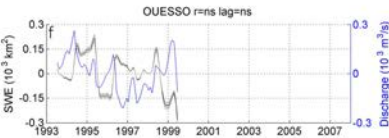
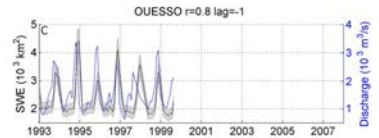
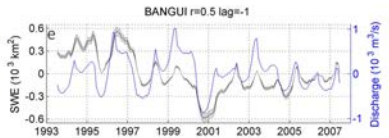
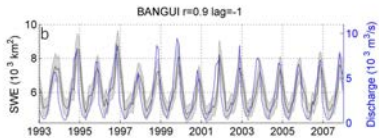
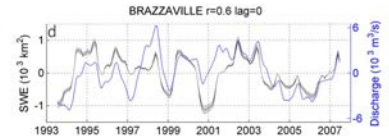
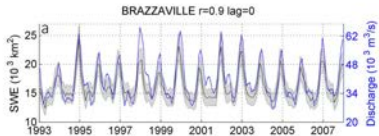
Fig.5

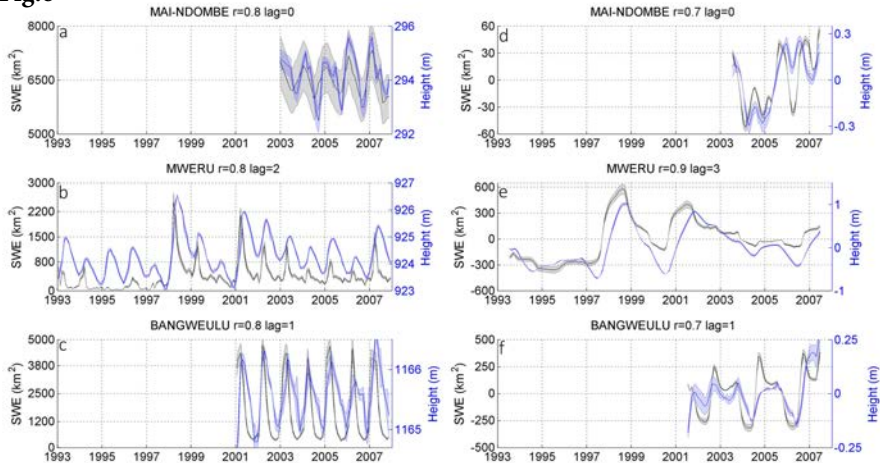
Fig.6

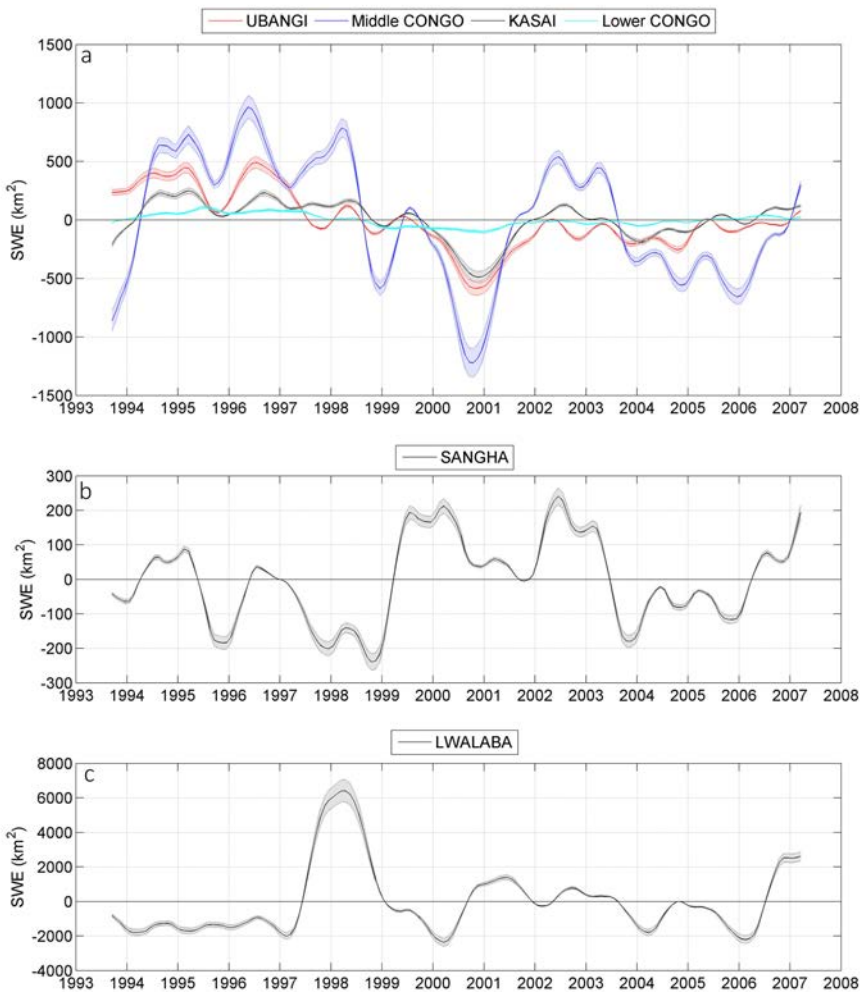
Fig.7

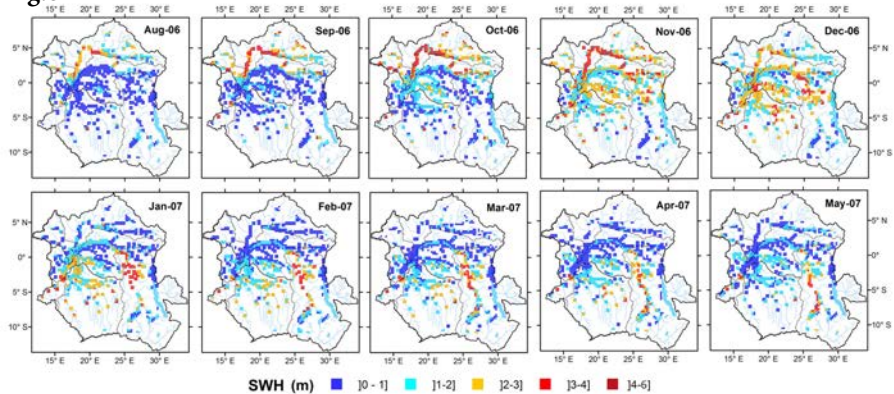
Fig.8

Fig.9

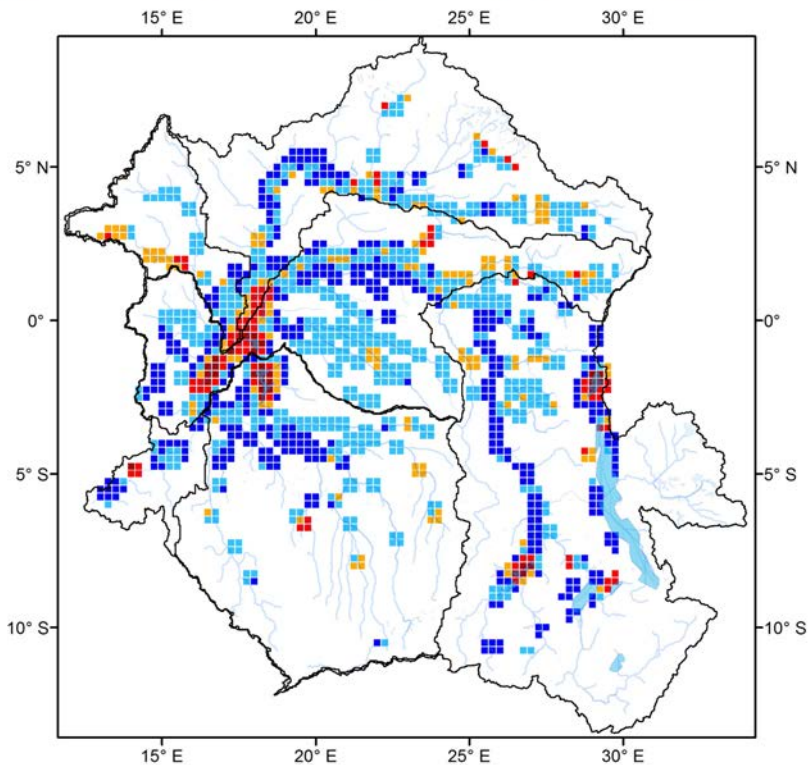
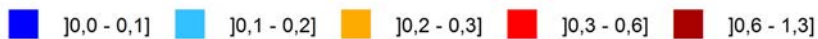
Maximum annual amplitude of SWS over 2003-2007 (km³)

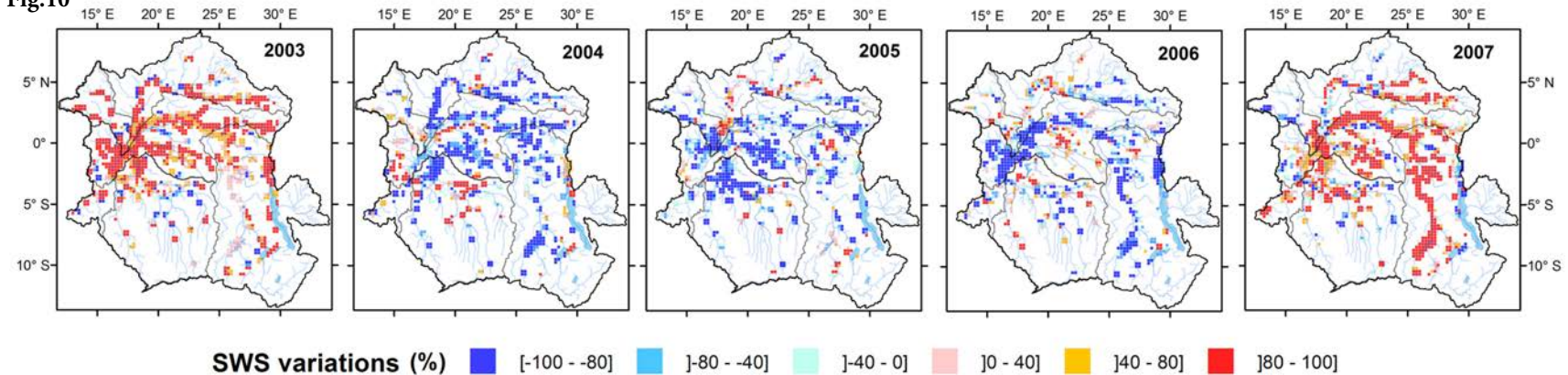
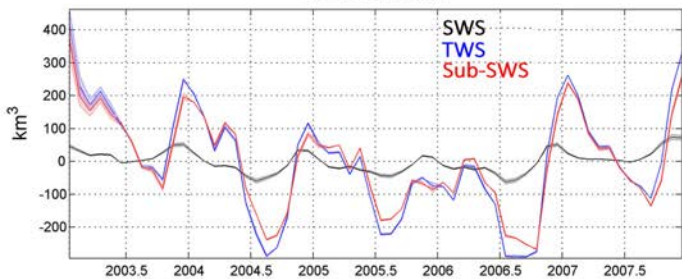
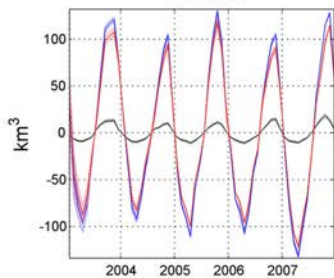
Fig.10

Fig.11

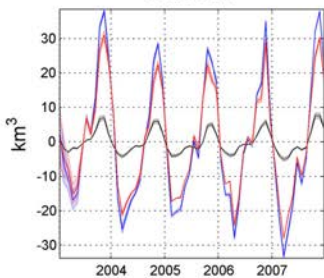
CONGO BASIN



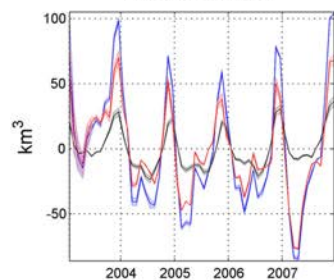
UBANGI



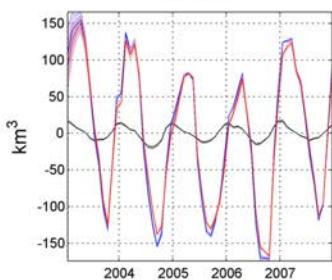
SANGHA



Middle CONGO



KASAI



LWALABA

