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# Characterization of terrestrial water dynamics in the Congo Basin using GRACE and satellite radar altimetry

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ABSTRACT

The Congo Basin is the world's third largest in size (~3.7 million km$^2$), and second only to the Amazon River in discharge (~40,200 m$^3$ s$^{-1}$ annual average). However, the hydrological dynamics of seasonally flooded wetlands and floodplains remains poorly quantified. Here, we separate the Congo wetland into four 3°×3° regions, and use remote sensing measurements (i.e., GRACE, satellite radar altimeter, GPCP, JERS-1, SRTM, and MODIS) to estimate the amounts of water filling and draining from the Congo wetland, and to determine the source of the water. We find that the amount of water annually filling and draining the Congo wetlands is 111 km$^3$, which is about one-third the size of the water volumes found on the mainstem Amazon floodplain. Based on amplitude comparisons among the water volume changes and timing comparisons among their fluxes, we conclude that the local upland runoff is the main source of the Congo wetland water, not the fluvial process of river-floodplain water exchange as in the Amazon. Our hydraulic analysis using altimeter measurements also supports our conclusion by demonstrating that water surface elevations in the wetlands are consistently higher than the adjacent river water levels. Our research highlights differences in the hydrology and hydrodynamics between the Congo wetland and the mainstem Amazon floodplain.


## 1. Introduction

The Congo Basin is the world's third largest in size (~3.7 million km$^2$), and second only to the Amazon River in discharge (~40,200 m$^3$ s$^{-1}$ annual average). The impact and connections of this hydrologic flux with the region's climate, biogeochemical cycling, and terrestrial water storage, especially in wetlands, is of great importance. For example, the extent of the differences in chemistry, seasonality, rate and volume of water input to the floodplain and wetland systems from upland runoff, direct rainfall and mainstem flooding are likely to supply substantially different amounts of nutrients and other solutes (Melack & Engle, 2009). However, the hydrological dynamics of seasonally flooded wetlands and floodplains remains poorly quantified through ground observations, satellite observations or modeling. As a consequence, estimates of the magnitude of other processes driven by such dynamics, such as methane emissions from flooded wetlands that form a significant contribution to global atmospheric methane, also cannot be well estimated. Given the vast size and remote location of the Congo Basin, satellite-borne observations provide the only viable approach to understanding the spatial and temporal distributions of its water balances.

Recently, Alsdorf et al. (2010) have estimated the amounts of water filling and draining from the mainstem Amazon floodplain using data from the Gravity Recovery and Climate Experiment (GRACE) and other satellite measurements. They showed that the majority of water on the mainstem Amazon floodplain is derived from the river with a much less amount from local upland runoff. However, there has been no attempt to estimate the Congo wetland water storage and its flux. In this study, we use satellite-borne observations to suggest a baseline measurement of these storages and fluxes by examining 1) the amount of water stored and drained from the Congo wetland, and 2) whether the water comes from rivers or adjacent upland areas.

We use total storage change in the form of equivalent water height (EWH) change (Wahr et al., 1998) from the GRACE measurements (Tapley et al., 2004), precipitation (P) estimates from the Global

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Precipitation Climatology Project (GPCP; Adler et al., 2003), evapotranspiration (ET) estimates from the Hillslope River Routing (HRR) model (Beighley et al., 2009), water elevation changes from Environmental Satellite (Envisat) altimeter measurements, and hydrological maps from HydroSHEDS (Lehner et al., 2008). Measurements of inundated area are made from a combination of (1) the Japanese Earth Resources Satellite-1 (JERS-1) Synthetic Aperture Radar (SAR) mosaics developed by the Global Rain Forest Mapping project (GRFM), (2) the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), and (3) Moderate-resolution Imaging Spectroradiometer (MODIS) mosaics (Jung et al., 2010a). Unfortunately, we have no available contemporaneous in situ discharge or water stage measurements. We combine these satellite-based measurements to: (1) estimate the wetland storage changes in four regions along the Congo mainstem and its major tributaries, and (2) determine whether the water comes from rivers or adjacent upland areas.

The methods presented here are improved compared to the previous study over the Amazon Basin (Alsdorf et al., 2010) because 1) HydroSHEDS is used to estimate the upland area that contributes directly to the wetland instead of using a ratio between estimates of upland area compared to the wetland area; 2) more realistic ET estimates are used instead of a single number representing the whole basin; and 3) a hydraulic analysis from altimeter measurements is also presented. We also use a longer time span (6 years compared to 2.5 years) of GRACE data.

## 2. Methods

### 2.1. Study area

We select four $3° \times 3°$ study regions to cover the wetlands of the Congo River mainstem and its major tributaries (Fig. 1). Study region 1 includes the Ubangi River (~3800 $m^3 s^{-1}$ annual discharge, Laraque et al. (2001)), which is the largest right-bank tributary of the Congo mainstem. Study region 2 includes the Sangha River (~1600 $m^3 s^{-1}$ annual discharge, Laraque et al. (2001)) and represents the majority of the northern tributary wetlands. Study regions 3 and 4 include eastern and southern tributaries, respectively. The box size is chosen based on the limit of the spatial resolution of GRACE which is determined from the maximum degree ($n_{max} = 60$) of the Stokes coefficients.

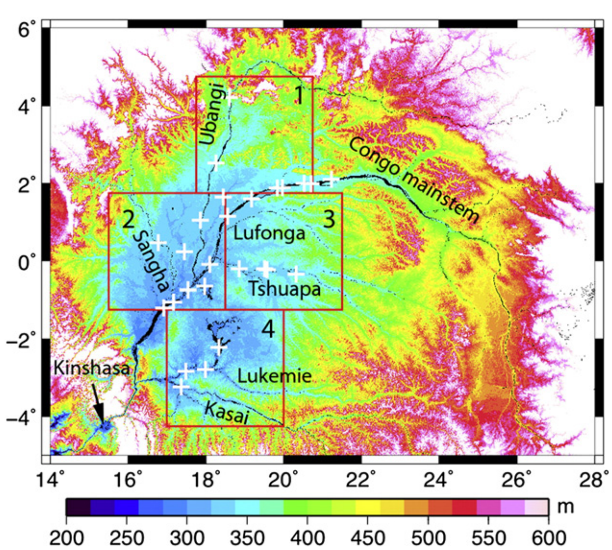


**Fig. 1.** Locations of four $3° \times 3°$ study regions in the Congo Basin. Background shows topography from the SRTM C-band DEM. Intersections between Envisat altimeter and the Congo River are indicated with "+".

### 2.2. Wetland storage changes from satellite measurements

Total storage changes for a given area, $\Delta S$, are a summation of the storage changes in wetlands ($\Delta S_w$), rivers ($\Delta S_r$), groundwater ($\Delta S_g$), and soil moisture ($\Delta S_{sm}$):

$$\Delta S = \Delta S_w + \Delta S_r + \Delta S_g + \Delta S_{sm}. \tag{1}$$

Measurements from GRACE provide $\Delta S$ in terms of anomalies with respect to a mean total storage value. We processed the Release 4 (RL04) Center for Space Research (CSR) GRACE Level 2 (L2) data product (Bettadpur, 2007) from January 2003 to December 2008. To reduce the GRACE longitudinal stripes associated with correlations among even or odd degree Stokes coefficients at resonant orders (Swenson & Wahr, 2006), decorrelation based on Duan et al. (2009) was used. We also applied smoothing using a 3-degree Gaussian filter (Guo et al., 2010). EWHs are computed at $1° \times 1°$ grid spacings, and spatially averaged over each study region. Finally, total storage anomalies are obtained by multiplying the EWHs by the box area. More details on the GRACE measurements are provided in Section 3.1.

The channel storage anomalies are estimated by multiplying water stage anomalies, obtained from the Envisat altimeter, with open channel areas estimated from the classification of GRFM image data (Table 1, see discussion below). The Envisat Geophysical Data Records (GDRs) contain 35-day repeat, 18-Hz data (twenty-measurements-per-frame), which corresponds to a ground spacing of approximately 350 m. The GDRs include range measurements from four different retracking algorithms. In this study, we use the retracked measurements from the ICE-1 retracker (Bamber, 1994), which generally performs well over inland water bodies (Frappart et al., 2006; Lee et al., 2010). The water stage anomalies over the intersections between the altimeter and the open water bodies are averaged for each tributary, and are then multiplied by the corresponding channel areas.

We use $2.5° \times 2.5°$ GPCP monthly merged precipitation rates $P(t)$ (Adler et al., 2003), and create anomalies by subtracting a linear fit, $\bar{P}$, to the integrated sum of $P(t)$ for each study region (see Alsdorf et al., 2010 for details). The slopes of the linear-fit lines represent six-year mean precipitation values, as summarized in Table 1. The GPCP data is derived partly from infrared and microwave satellite measurements, and it should be noted that, as stated in Beighley et al. (2011), there is a discrepancy between various satellite derived precipitation datasets over the Congo Basin in terms of their magnitudes, especially in equatorial regions, which correspond to study regions 2 and 3 in this study. For ET, we use model-based estimates from HRR. It is the sum of wet canopy evaporation, dry canopy transpiration and evaporation from saturated soil surfaces based on the potential ET using Penman–Monteith indirectly through the temperature-based method of estimating its data sources (see Beighley et al., 2009, 2011 for details). The ET rates over each Pfafstetter Level 4 sub-divisions are averaged for each of the four study regions ($\bar{E}$) (Table 1). This Pfafstetter discretization frame-work is a natural system, based on topographic subdivision of the land surface and the resulting topology of the hydrographic network (Verdin & Verdin, 1999). Each level of discretization results in 9 sub-divisions (i.e., 4 tributaries and 5 local contributing areas to the

**Table 1**
Hydrologic and geomorphic characteristics of each study region.

| | Region 1 | Region 2 | Region 3 | Region 4 |
|---|---|---|---|---|
| Upland ($km^2$) | 83,605 | 42,905 | 55,297 | 58,587 |
| Wetland ($km^2$) | 28,052 | 68,596 | 56,360 | 52,914 |
| Channels ($km^2$) | 1058 | 3990 | 502 | 2766 |
| Annual P ($m\ year^{-1}$) | 1.44 | 1.53 | 1.87 | 1.71 |
| Annual ET ($m\ year^{-1}$) | 0.90 | 1.01 | 1.06 | 0.92 |
| Contributing area ($km^2$) | 121,330 | 151,596 | 152,789 | 141,728 |