Long-term Hydrological Variations of the Ogooué River Basin

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Abstract: This chapter describes the variability of rainfall and river discharges in the Ogooué River basin (ORB) in recent decades (since 1940). Due to its location crossing the Equator, the ORB receives abundant precipitation that maintains one of the world's best-preserved ecosystems. In contrast to neighboring forest basins that have been severely degraded because of deforestation, mining resources extraction, extension of agricultural areas and river transport, which is a crucial alternative to the cruel lack of road infrastructures, the ORB is experimenting an exceptional conservation policy in the region. For example, the rural penetration rate in

Gabon is about 1 inhabitant per km^2 and many studies report a deforestation rate close to 0%, with even full natural regeneration. However, the fluctuations of the standardized anomaly index of rainfall in the ORB show three main phases of variations: the first wet phase was characterized by abundant precipitations from 1940 to 1970, the second phase of long-term mild drought was extended in 1970s and 1980s and the final third phase presented a slight return of abundance in precipitation. Even though drought severity in the ORB was mainly weak, its effects in river discharges were very sensitive in seasonal and inter-annual scales. The pure equatorial regime of the ORB characterized by equal maximum floods in spring and autumn changed significantly from the difference between both maximum discharges of 13.5 % during the 1960s to 27.0 %, 38.4 %, 33.9 % and 26.7 % for the 1970s, 1980s, 2000s and 2010s respectively. A brief comparison between the ORB and the Congo River basin showed that changes in the ORB are part of a regional process that Central Africa is undergoing with some spatial heterogeneities.

Keywords: Central Africa; deforestation; drought; hydrological variations; the Ogouué River basin.

1 Introduction

The Ogooué is one of the major rivers in central Africa as it ranks second in terms of river discharge, only preceded by the Congo River. The Ogooué River annual average discharge is around 4,700 m^3/s in a drainage basin of the area around 224,000 km^2 (Kittel et al., 2018). Approximately 90 % of this drainage area is located in Gabon, covering more than 80 % of the total country area while the remaining 10 % of the Ogooué River Basin (ORB) is located in Cameroon and Congo Republic. Almost the whole ORB is covered with dense vegetation of the central Africa rainforest. Several national and international areas of great importance, such as national parks (Lopé National Park , Ivindo National …), marine protected areas and RAMSAR sites (the Rapids and Chutes of the Ivindo, or the Mboungou Baduma and the Doumé Rapids) (Cutler et al., 2016; Cutler et al., 2019) can be found in the ORB. Les Portes d'Okanda, shown in Figure 1, are inscribed on UNESCO's Natural Heritage List. Owing to these different conservation measures, the ORB is one of the most preserved ecosystems in Central Africa.

However, the ORB probably experienced very deep climatic changes some decades ago. Numerous authors pointed out some recent climatic and induced environmental changes in West and Central Africa magnified by the generalized decrease in precipitation and hence the decrease in streamflow in river basins at regional scale (Servat et al., 1997; Paturel et al., 1997; Mahé et al., 2005; Lienou et al., 2008; Nguimalet, 2018). According to Mahé et al. (2005), the rainfall deficit in equatorial Africa is not long enough to have a lasting impact on interannual rainfall regimes. In return, critical decreases in river discharges have been observed in several river basins in west and central Africa (Laraque et al., 2001; Mahé et al., 2005; Lienou et al., 2008; Mahe et al., 2013; Nguimalet, 2018; Nguimalet & Orange, 2019). It seems therefore crucial to carry out analyses on the variability of hydroclimatic parameters in recent decades in order to understand the changes prevailing in the ORB. We present here a first review of the current knowledge about the hydrology, climate and carbon fluxes over the Ogooué River from litterature and analysis of some recent data, and give some direction for future studies.

2 Geography of the Ogooué River Basin

The Ogooué River Basin (ORB) is located on the west Atlantic coast of central Africa and is crossed by the equator. Its geographical location ranges between latitudes 3°S and 2.5°N and longitudes 9°E and 14.5°E (Figure 2). It is encompassed to the north and northwest by the coastal basins of the Ntem and Komo rivers respectively, to the east by the Congo Basin and to the south by the Nyanga and Niari basins (Mahé et al., 1990). ORB's landscape is mainly mountainous, although the heights are not very significant, having an average altitude of about 450 m (Kittel et al., 2018). Three main topographical structures are encountered in the basin: (1) The low coastal plain, which extends from the mouth of the river to the Atlantic Ocean and covers the lakes region and the Ogooué delta; (2) The plateaus, sometimes heavily cut out by rivers, encountered in most of the surface area of the basin; they extend northwards over Ogooué-Ivindo, south-east over Haut-Ogooué (the Batéké plateau), southwards over the Ogooué-Lolo and Ngounié regions. (3) The mountainous massif inside the basin constituted by medium-sized mountains that form real chains (this is the case of the Chaillu massif in the centre, some of whose peaks reach 1000 m) (Giresse, 1990).

The highest peaks of the ORB are: Mount Bengoué (1070 m) located northeast of the ORB in Ogooué-Ivindo, Mount Milondo (1020 m) located between the Ngounié and Ogooué-Lolo, Mount Ngour Mikong (993 m) in the Moyen-Ogooué, Mont Iboundji (980 m) in Ogooué-Lolo, Mount Belinga (895 m) in Ogooué-Ivindo, Mount Mimongo (860 m) in Ngounié, Mount Boka Boka (857 m) in Ogooué-Ivindo, Mount Kumunabwali (833 m) in Ngounié (CBD, 2004).

The Ogooué River and its tributaries drain various geological and morpho-pedological contexts (Guillocheau et al., 2015) and feed the sedimentation zones of the passive margin of Central Africa. The formation of flattened surfaces seems to have presided to the shaping of the relief as in other regions of Africa, but later overall upheavals and excavations linked to the lowering of the sea level allowed normal erosion to profoundly modify this type of landscape (Martin et al., 1981). The main landscapes are explained by intact or dissected flattened surfaces, mountainous areas raised by ancient or recent tectonics and the diversity of geological rocks.

The coastal sedimentary basin of the ORB is a hydromorphic region in the flattened area below 200 m in altitude that contrasts with the mountainous part of the craton. From Lambaréné to the coast, passing through the lakes and lagoons of the Ogooué delta, there is a particular landscape linked to the preponderance of water. Strong local heterogeneity is caused by the nature of the bedrock, composed of sandstone to argillite and marl, the presence of thin soils and the variable density of the drainage network associated with high rainfall (Martin et al. 1981).

3 Precipitation of the Ogooué River Basin

Due to its position in equatorial Africa, the Ogooué Basin (ORB) receives significant amounts of rainfall in the year (1600-2200 mm/yr) (Lambert et al., 2015; Mignard et al., 2017). The climate of the ORB is equatorial, characterized by a bimodal rain pattern with two dry seasons and two rainy seasons (Mahé et al., 2005; Kittel et al., 2018). The annual average rainfall over the basin is about 1630 mm during the XXth century (Mahe et al., 2013). Given the uneven distribution of rainfall during the rainy seasons, there is a small rainy season between March - April - May (MAM) and a large rainy season between October - November - December (OND). These seasons alternate with the dry seasons also known as the small and large ones in boreal winter and summer respectively. Although it is very rare to find studies that have focused specifically on ORB rainfall, many authors have analyzed rainfall variation on areas including ORB in studies at the national (Maloba Makanga, 2015; Mahé et al. 1994), regional (Balas et al., 2007; Nicholson et al., 2012; Dezfuli & Nicholson, 2013; Nicholson, 2018), and at the continental level (Nicholson, 1986; Nicholson & Entekhabi, 1987; Nicholson et al., 2018). Several studies on precipitation in equatorial Africa including ORB have either highlighted ongoing climate change in this region (Olivry et al., 1993; Sonwa et al., 2014) or demonstrated the links between local precipitation variability and the main drivers of major global changes including tropical ocean SST (Balas et al., 2007; Nicholson et al., 2012; Dezfuli & Nicholson, 2013) and the North Atlantic Oscillation (NAO) (Todd & Washington, 2004). A salient feature that should be highlighted is the recent demonstration of the independence of rainfall variations in Equatorial Africa on the meridian transits of the Intertropical Convergence Zone (ITCZ) (Nicholson, 2018).

However, rainfall variations in the ORB are still poorly understood. This is due to the lack of reliable long-term data to conduct accurate studies in the region (Nicholson et al., 2018). The number of operating rainfall stations has decreased considerably in Central Africa in general (Rouché et al., 2010; Alsdorf et al., 2016; Nicholson et al., 2018) and in the ORB in particular where almost no rainfall data has been recorded since the end of 1990 (Maloba Makanga, 2015). Fortunately, the almost global availability of satellite precipitation data enables continuous monitoring of rainfall, making it possible to avoid gaps in long term records caused by the cessation of in situ stations operation and to build reliable databases across the African continent (Boyer et al., 2006). The rainfall data used in this study come from the 0.5 X 0.5 degree grid of monthly precipitation for the African continent generated from the reference series inherited from observations of the ORSTOM (Office de la Recherche Scientifique et Technique de l'Outre-Mer, now Institut de Recherche pour le Développement - IRD) and now on free access at the SIEREM (Système d'Informations Environnementales sur les Ressources en Eau et leur Modélisation) website of Hydrosciences Laboratory Montpellier (HSM) (Rouché et al., 2010; Dieulin et al., 2019). These data cover the period 1940 – 1999 and are available at http://www.hydrosciences.fr/sierem/produits/index.asp?frame=grille. The SIEREM database was developed by hydrologists from the HSM laboratory in order to preserve and make available to the scientific community the huge amount of data collected by the ORSTOM Institute during several decades in Africa, completed by data coming from the FRIEND program of UNESCO (Van Lanen et al., 2014). These data come from National services of all African countries and thus are supposed to have been previously checked by national services. They were however double-checked and criticized to remove all suspicious and erroneous data. This was achieved by a first automatic check of values, followed by a manual comparison with neighboring stations. This data base eventually contents more than 6,000 stations, which is twice more than the CRU database over the same area, with more data in all areas of the continent, where the CRU database shows some regions with very poor coverage. A map of the differences between CRU and SIEREM data, as well as a quantitative assessment for several areas, has been performed and presented by Dieulin et al. (2019). It shows that the SIEREM database better represents the observed precipitations, at continental scale. Mahe et al. (2008), performed a comparison of the performances of hydrological modelling according to several input rainfall data (CRU, SIEREM and raw data from the national services) in West Africa. Better results in terms of discharge estimates were obtained using SIEREM than CRU or to raw-unchecked- data from national services.

We thus used the SIEREM database to analyze the rainfall data in this study . The SIEREM database used data acquired after 1940, due to the lack of a sufficient number of in-situ stations before 1940, to interpolate the gauge records at monthly time scale to allow a good description of the local rainfall variability. On the contrary, the CRU database provides gridded anomalies derived from a less numerous number of in-situ stations and considering the period 1960-1990 as a reference, which is not the case of the SIEREM database, for which each monthly grid is calculate from the available observed data each month, with no reference period used.

To start the analysis of precipitation in the ORB during the six decades with available data, the annual average rainfall maps for each decade were represented (Figure 3). It can already be seen that, over this period, the spatio-temporal distribution of the rainfall in the ORB exhibit minima of ~ 1400 mm/yr in the south during the 1940s and the east during the 1960s and maximum of ~

2300 mm/yr in the west during the 1940s and the 1990s. Considering the spatial distribution of rainfall in the ORB over the whole period, a zonal gradient is observed with maximum rainfall occurring in the coastal part on the west of the basin. This observation is not surprising since the ORB is located in the coastal zone, apart from local recycling, the moisture needed for precipitation in the basin is provided through advection on the nearby ocean surface (Dezfuli, 2017). This last assertion represents only part of the Atlantic Ocean's contribution to the ORB's precipitation. More than proximity, it is the tropical Atlantic Sea Surface Temperature (SST) the main driver of precipitation variability in West Equatorial Africa including the ORB (Balas et al., 2007; Nicholson & Dezfuli, 2013; Dezfuli & Nicholson, 2013; Hua et al., 2016; Nicholson et al., 2018). SST participates in the supply of humidity, but also in its transport through the monsoon zone (Roxy, 2014). Moreover, even if the differences are not obvious, these maps show a decrease in precipitation over the entire basin during the 1970s and 1980s compared to the other four decades, the 1970s being obviously the most affected. This suggests a temporal variability in precipitation in the ORB at the interannual scale may even be at the ten-year scale.

The temporal variability of precipitation in the ORB during these six decades of observation was also analyzed. First, the basin-scale precipitation time series termed $\delta h(t)$ was estimated using the equation (Ramillien et al., 2006)

$$\delta h(t) = \frac{R^2}{S} \sum_{j \in S} h\left(\lambda_j, \theta_j, t\right) \sin\left(\theta_j\right) \delta\lambda \, \delta\theta \qquad (1)$$

where $h\left(\lambda_j, \theta_j, t\right)$ is instantaneous local monthly rainfall, expressed in mm per month, with $j = 1, 2, 3, \ldots, N$, $S$is the area of the basin, λ_j and θ_j are longitude and latitude, $\delta\lambda$and $\delta\theta$ are the grid steps in longitude and latitude (generally $\delta\lambda = \delta\theta$, $S$is the surface area of the basin and

R the mean radius of the Earth ~ 6371 km)

The annual precipitation time-series is presented in Figure 4. The annual variations of rainfall in the ORB over the period of observation range from ~2000 mm to ~2500 mm. Certainly, the amplitude of the variation of about 500 mm may seem very important, but the interannual variability is not as significant as it was expected according to some studies Mahé et al., 2005; Lienou et al., 2008; Mahé et al., 2013. The standard deviation of the interannual variation in precipitation over the basin represents only 7.1 % of the annual average precipitation in the ORB. This range of variation is comparable to that recently determined using data from the Tropical Rainfall Measurement Mission (TRMM) satellite TMPA-3B42 V7 over the period 1998-2015 (Bogning et al., In press). Over the entire observation period, the interannual variations exhibit a small amplitude in the ORB, similarly to what was observed in other basins located in equatorial Africa (Mahe et al., 2013). In addition, Figure 4 also shows the seasonal decomposition of the annual rainfall in the ORB in every season of the year. The difference between the rainy and dry seasons corresponds to a significant decrease in precipitation.

However, despite the small changes in interannual rainfall variations, it is important to look at the effects of these changes over the long term. Some studies have reported the occurrence of a severe drought in Central Africa for almost five decades using rainfall data using more than one thousand rain gauges of the Atlantic coastal area of Africa (from Senegal to Angola) (Olivry et al., 1993) or using around 250 rain gauges within the Congo and its neighboring river basins (Laraque et al., 2001). Recent studies took advantages of observational and multi-approach modelled gridded datasets (Hua et al., 2016); (Hua et al., 2018). Even National Services datasets were used, supplemented by others collected partly during research programs (e.g. AMMA/EU; RESSAC/ECLIS/ESCAPE/French National Research Agency; SIGMED/AUF program) (Mahé et al., 2005; Mahé et al., 2013). While some of these efforts have provided information on rainfall changes in the ORB, the basin-focused studies are lacking in the literature. The standardized anomaly index (SAI) was used to understand the plausibility of the signal of this drought on the ORB. The SAI is a commonly used index for regional variability of some climate parameters (Koudahe et al., 2017). Ithas been widely used to assess drought severity in tropical areas (Kraus, 1977; Lamb, 1982; Katz & Glantz, 1986; Naresh Kumar et al., 2009; Frappart et al., 2013; Chanda & Maity, 2015). SAI was defined as follows in Kraus (1977) and Lamb (1982):

$$SAI = \frac{1}{N} \sum_{j \in S} \frac{h(\lambda_j, \theta_j, t) - \overline{h(\lambda_j, \theta_j)}}{\sigma(h(\lambda_j, \theta_j))} \quad (2)$$

where $h(\lambda_j, \theta_j)$ is local monthly rainfall, expressed in mm per month, with $j = 1, 2, 3, \ldots, N$, $S$is the area of the basin, λ_j and θ_j are longitude and co-latitude and $\sigma(h(\lambda_j, \theta_j))$ is the standard deviation of local monthly rainfall.

The SAI makes it possible to classify drought as presented in Table 1 below (Mc Kee et al., 1993; Naresh Kumar et al., 2009):

Since the occurrence of drought affecting some regions of the ORB can be masked by abundant precipitations of other regions, the delineation of zones exhibiting homogeneous rainfall variability was carried out. Authors used several approaches for the regionalization of hydroclimatic data. Among these, the most widely used are regression analysis (LeSage, 1997; Vogel et al., 1999; Swain and Patra, 2017) and the spatial proximity approach for the regionalization of watershed flows (Merz and Blöschl, 2004; Parajka et al., 2005; Masih et al., 2010; Samuel et al., 2011). These different methods aim at identifying different homogeneous regions of hydroclimatic parameters. In this study, the k-means clustering was not only used to determine the number of homogeneous regions but also their spatial location. Each region is defined using a regionalization vector grouping the zones or stations with the same interannual variability of precipitation.

The approach of the k-means clustering algorithm is to decrease or minimize the quadratic error between the empirical mean of a cluster and the cluster point (centroid) (1). This quadratic error is given by the following relationship :

$$J(C_k) = \sum_{x_i \in C_k} \|x_i - \mu_k\|^2 \qquad (3)$$

where $\{x_i\}_{i=1,\dots,n}$ is the grid variable, μ_k is the mean of the cluster group, C_k , $J(C_k)$ is the squared error of the cluster C_k .

To minimize the sum of the squared errors of all K clusters, the following formula is used:

$$J(C) = \sum_{k=1}^{K} \sum_{xi \in C_k} \|x_i - \mu_k\|^2 \quad . \qquad (4)$$

The homogeneous rainfall zones based on SIEREM rainfall datasets are presented in Figure 5. the first delineated area is the low coastal plain characterized by very high precipitation. Annual rainfall on this part of the ORB generally exceeds 2000 mm. The second zone begins along the Crystal Mountains and extends to the northeast on Mount Batouala and the northeast plateau. The third zone covers the Batéké Plateau and extends northward on the Boka Boka massif in Ogooué-Ivindo.

The time variations of the SAI in the three delineated zones of the ORB from 1940 to 1999 are presented in Figure 6. These SAIs shows that drought years (SAI < 0) were recorded in all decades of the six observed in the ORB. There is almost an equal distribution between wet and dry years out of the 60 observed. In addition, it can be seen that, unlike alternating rainy and dry years with no more than four consecutive dry years before the 1970s, there were long-term drought periods from 1971 onwards in all the three delineated zones. The 1970s and 1980s showed very long drought periods that diversely occurred in the zones of the ORB and have been generally reported in regional studies (Olivry et al., 1993; Bigot et al., 1996; Mahé et al., 2005). The distribution of years by categories according to the SAI values in the different zones of the ORB is given in Table 2. It can be seen that although there are changes, they are very small, with years of slight drought and humidity representing more than 83% of the study period for all three rainfall regions of the ORB. In addition, the results of the Mann-Kendall (Mann, 1945; Kendall, 1975) test on SAIs, based on a python package for non-parametric Mann-Kendall family of trend tests (pyMannKendall) (Hussain and Mahmud 2019), shows that no trend can be derived (the estimated trends are not significant) from the calculated SAIs in these three regions. In summary, the Ogooué Basin experienced a long drought in the 1970s and 1980s, followed by a slight recovery in the 1990s like most regions of humid central and west Africa. However, this drought has not been as severe in the ORB as in other Central African river basins such as the southern Cameroon basins (Sighomnou et al., 2007; Lienou et al., 2008) and the Oubangui basin (Laraque, 1998; Nguimalet et al., 2016). In turn, besides the fact that it seems to be returning in the 1990s, the local rainfall abundance observed before this long dry period has not yet been restored.

4 Ogooué River Basin Hydrographic Network

4.1 Main rivers of the Ogooué River Basin

The Ogooué River originates in Congo, in the Mounts Ntalé at an altitude of nearly 840 m. It initially flows in a northwest direction through the Batékés plateaus before moving westerly from the equator to its mouth in the Atlantic Ocean. Its total length, from its source to the Atlantic Ocean, is about 1200 km (Kittel et al., 2018). Its basin is drained by a dense hydrographic network with about one river every 600 m. These main tributaries in order of flow importance are the Ivindo, which flows into the Ogooué from the right bank close to the equator at Kankan, and the Ngounié, which flows into the Ogooué from the left bank a few dozens of kilometers upstream from Lambaréné. The Ivindo River originates in northern Gabon, not far from the Congolese border and drains the northeast of the ORB. It is covered with vast tracts of virgin forests, often primary. It runs about 500 km before flowing into Ogooué. The Ngounié River originates in the southwestern part of Gabon on the Congolese border. It drains the large forest plain between the Chaillu massif and the Ikoundou mountains. The other tributaries of the Ogooué are on the right bank the Mpassa, the Lékoni, the Sébé, the Lassio, the Okano and the Abanga and on the left bank the Leyou, the Lolo, the Offoué (Figure 2) (CBD Second National Report - Gabon 2004).

4.2 Lakes and wetlands in the Ogooué River basin

The main lakes of the ORB are located in the lower reaches of the Ogooué River around its inland delta. On the left bank of the river are lakes Ezanga, Oguemoué and Onangué, the largest lake in the basin. And on the right bank are lakes Azingo, Gomé and Opindalwango (Ondo, 2012). In the Ngounié Basin, in the region between Mouila and Ndendé, there are many small karst lakes such as Black Lake and Blue Lake and between Fougamou and Gamba are the Goumba, Divangui and Kivoro. The wetlands are primarily found in the inner delta of the Ogooué between Lambaréné and the outlet of the Ogooué River in Port-Gentil. They cover an area of 13,700 km². The Ogooué inner delta has been listed as a RAMSAR World Heritage Site of International Importance under the name Ramsar Bas-Ogooué since 2009. The Kongou Falls on the Ivindo River are emblematic wetlands in the northeast of the ORB. These falls, of more than 2 km wide, descend in 3 successive jumps of about 80 to 100 m of vertical drop (Figure 7). It is an important tourist area. The Mboungou-Badouma and Doumé Rapids on the Ogooué River and at the confluence between the Ogooué and the Sébé River, which are also classified as RAMSAR international wetlands. This RAMSAR zone stretches over an area of approximately 2 km wide and 140 km along the Ogooué River, for a total of 595 km² of protected site between the provinces of Ogooué-Lolo and Haut-Ogooué (Cutler et al., 2016; Cutler et al., 2019). It is a hotspot of Gabonese ichthyology. In this region, Alfred Marche discovered 10 new fish species in 1856. A recent ichthyological exploration by Gabonese and international teams permitted to discover 9 new species (Cutler et al., 2019).

5 Discharge of the Ogooué River basin

The first discharge measurements of the Ogooué River date back to 1930 (Mahé et al., 1990). It was achieved in Lambaréné. Before 1960, the ORB had slightly over forty hydrological stations dedicated to monitoring river flows in the basin (Carré, 1978). These stations provided the quantitative information necessary for the proper monitoring of the hydrological cycle in the ORB. The data collected by these stations were recorded in the hydrological yearbooks in the ORSTOM section in Libreville. After the independence of African countries in the 1960s, the stations gradually came under the control of local governments and they did not keep pace with the maintenance of the stations. Data collection in African monitoring networks became sparse and, by the 1980s, almost all hydrometric stations in the ORB were at a standstill. Fortunately, SIEREM saved most of the hydro-climatological data from the former ORSTOM Hydrology Laboratory. These data were enriched and updated during the various research programs developed by the team, first at the Hydrological Antenna in Abidjan (1987-1998) and then at HydroSciences Montpellier in a second phase (1999 to the present) (Boyer et al., 2006). Ogooué data have also been reconstructed by Mahé et al (1990). The longest series of the Ogooué River discharge available today is that of the Lambaréné station (Figure 8). This station measures the Ogooué discharge for drainage of more than 90% of the ORB (Mahé et al., 1990).

Figure 8 presents the temporal variations of the annual discharge of the Ogooué at Lambaréné from 1930 to 2016. Very large inter-annual variations of about 3000 m^3/s are observed in the annual average discharge time series of the Ogooué River. The highest streamflow values were recorded during the 1930s and 1940s. Significant decreases in river discharge have been recorded since the 1950s, with very low annual discharge observed in 1958 and 1983. These variations certainly accompany those of the precipitation mentioned above with much more pronounced effects. The largest decreases recorded correspond to the years of severe drought mentioned above. Also, it can be seen that the 1970s and 1980s are the most deficient decades in water flow in Lambaréné, because of very low rainfall during the same periods. And all this is part of a general trend observed on the rivers of Central Africa during this period (Olivry et al., 1993; Laraque et al., 2001; Mahé et al., 2005; Mahé, 1993; Mahe et al., 2013). The evolution in the 1990s should be taken with some caution because during this decade, the flow of the Ogooué was not monitored and the data used are very often derived from reconstructions (Mahe et al., 2013). Overall, the SEEG (Société d'Énergie et de l'Eau du Gabon) measurements made it possible to continue observation from 2001 onwards and it can be seen that the Ogooué module never again reached the highest values recorded before the 1970s. In equatorial areas, hydrological regimes are directly related to the rainfall so that all variations in rainfall have a direct impact on local river flows (Bricquet, 1990). As the ORB is a coastal basin, relatively small (compared to the large basins of the Congo or the Amazon), the delays between rainfall events and their induced effects on river discharges are very small or practically null.

However, even if the variations in streamflow follow those of the rainfall, their fluctuation are more pronounced than those of rainfall and it is necessary to seek for possible explanations of this. Further investigations on hydrological drought in the ORB were carried out based on runoff coefficient time series. The runoff coefficient is a dimensionless parameter relating the amount of runoff to the amount of precipitation received. This parameter depends on the nature of the land surfaces, the degree of saturation of the soils, the slope, and the rainfall intensity. Also, it can be influenced by the proximity to the water table, the porosity of the soil, the vegetation, the degree of the soil compaction, and the depression storage (Goel, 2011). Annual variations of the runoff coefficient in the ORB are shown in Figure 9. Low values of the runoff coefficient denoted a well vegetated area as the ORB is. However, in spite of the strong interannual fluctuation, the overall trend is decreasing, even though the vegetation cover, although well preserved, certainly did not increase between 1940 and 1990. And even though the decrease in heavy rainfall in the region has been discussed (Aguilar et al., 2009), the reason of the variation in this coefficient is to be found elsewhere. In addition, correlation between rainfall and river discharge at Lambaréné was found to equal to 0.67 with a p-value close to 0 (7.31×10^{-8}). This significant correlation demonstrates the strong covariation of rainfall and river discharge in the ORB without dissipating the plausible implication of another phenomenon. Here it might be interesting to investigate which role might play an increase in air temperature, as scheduled and globally observed over the globe, which could increase slowly the evaporation demand and reduce then the soil water available for runoff. Another possible linked variable could be a change in the cloud cover, which if decreasing would increase evaporation. These two possible causes linked to the observed decrease of the runoff coefficient could be investigated later on in a further study, within the teams of the DYCOFAC International Laboratory in Yaounde, Cameroon.

The Ogooué rainfall regime is considered perfectly equatorial, i.e., the two rainy seasons of spring and autumn are similar (Lachiver, 1963). However, many studies have revealed significant differences between spring and fall floods (Lienou et al., 2008; Mahe et al., 2013). Figure 10 shows the hydrograph of monthly flows by decade of the Ogooué in Lambaréné; it clearly appears that high water discharge variations are more pronounced in spring than in autumn. In addition, during the 1970s and 1980s, which exhibited significant rainfall deficits and therefore flow deficits, flows declined considerably in the spring and not so much in the autumn. The difference between both maximum discharges changed from 13.5 % during the 1960s to 27.0 %, 38.4 %, 33.9 % and 26.7 % for the 1970s, 1980s, 2000s and 2010s respectively. This last observation is not really visible in the variation of precipitation.

To find out whether the observed asymmetry in the two flood seasons is a simple effect of the variability of precipitation, covariations of rainfall, river discharge and runoff coefficient were analyzed. Figure 11 shows the interannual variations in rainfall, river discharge and runoff coefficient in both flood seasons. On the one hand, the rainfall tend to be larger in autumn than in spring, as does the river discharge, as seen above. On the other hand, the runoff coefficients, while similar before 1970, decreased a little more in spring than in autumn from 1970 to 1990. The fact that the decrease in precipitation has resulted in a greater decrease in river discharge in spring may be partly related to somewhat large decrease in the runoff coefficient in this season than in autumn.

A study by (Makanga & Samba, 1997) highlights the different rainfall dynamics between the north and the south of the ORB depending on whether one considers the spring or autumn rainy season. This study highlights the fact that the spatial homogeneity in terms of precipitation in the coastal zone at the eastern corner of the Gulf of Guinea including the ORB advocated in some studies (Nicholson, 1980; Nicholson & Dezfuli, 2013; Dezfuli & Nicholson, 2013; Nicholson et al., 2018) is most realistic during the OND rainy season. (Makanga & Samba, 1997) showed a more pronounced drought trend in northern ORB than in the southern part of the basin from the 1970s onwards. With regard to floods, the decrease in boreal spring flows during the 1970s and 1980s is widespread in the ORB, but is most pronounced in the northern part of the Ivindo. In contrast, fall flood flows increased significantly in the 1970s and 1980s in the northern part of the ORB and not south of it (Lienou et al., 2008).

To summarize, from the 1970s onwards, in the northern part of the ORB, the pure equatorial regime characterized by similar spring and autumn flood maxima slightly shifted to a northern equatorial regime, while the two floods remained of identical amplitude in the southern part, suggesting a pure equatorial regime (Lienou et al., 2008). These regime changes in western equatorial Africa have been linked to poor rainfall conditions of monsoon flow during northern ITCZ migration (Citeau et al., 1988; Citeau et al., 1989; Mahé et al., 1990) and SST anomalies in the south-eastern equatorial Atlantic Ocean (Mahé & Citeau, 1993). However, the decrease in rainfall intensities is not enough to account for these very intense changes in river flows. Indeed, the critical decrease in river discharges in boreal spring in the ORB is due to the seasonal distribution of rainfall as it is a result of the reduction in January and February rainfall which leads to a higher soil moisture deficit than before, and the rainfall in the following rainy season compensates for this deficit before generating runoff (Lienou et al., 2008).

6 Carbon fluxes of the Ogooué river

Soil, atmosphere and ocean are the three large carbon reservoirs that global rivers connect (Li et al., 2017). Riverine carbon can be classified into four forms, according to solubility and biodegradation: dissolved organic carbon (DOC), particulate organic carbon (POC), dissolved inorganic carbon (DIC) and particulate inorganic carbon (PIC) (Meybeck, 1993; Li et al., 2017). DOC enrichment in rivers water is naturally controlled by soil leaching, DIC by carbonate mineral weathering and atmospheric and soil CO_2, POC by soil erosion, sedimentary rocks and autochthonous, and PIC by autochthonous and sedimentary rocks (Meybeck, 1993). Soil organic carbon originates from atmospheric CO_2 *via* plant photosynthesis and is then transported into the soil organic carbon pool in the form of litter (Li et al., 2017); and a portion of soil organic carbon is completely decomposed and dissolved as DOC, which then leaches into rivers with soil water. In tropical forestry environment, vegetation degradation largely contributes to the DOC transfer (Dupré et al., 1999; Oliva et al., 1999; Braun et al., 2005; Sekhar et al., 2008). The origin of organic matter (OM) in Ogooué basin is both marine and terrestrial, with a higher contribution of continental source *versus* marine source (Biscara et al., 2011). The OM predominantly derived from terrestrial land plants and has not been subjected to intense oxidation. It is characterized by a high hydrocarbon potential (Biscara et al., 2011). Land cover in Ogooué Basin, as noticed for tropical freshwaters, plays a primary role in controlling DOC concentration and optical properties knowing the capacity for absorbing sunlight irradiance (Lambert et al., 2015). Indeed, higher cover of dense forest in the catchment leads to a higher quantity of highly aromatic dissolved organic matter (DOM) network, contrary to savannah cover where DOC concentration is lower and the one of DOM less absorptive.

The carbon flux transported every year from the land to the ocean by the world rivers is approximately 1.06 Pg, of which 45% is organic including 0.23 Pg DOC and 0.23 Pg POC, and 55 % is inorganic including 0.39 Pg DIC and 0.18 Pg PIC (Li et al., 2017). These values are very close to the previous which revealed that global rivers export approximately 1 Pg C to oceans every year, of which 40% is organic including 0.22 Pg DOC and 0.18 Pg POC, and 60 % is inorganic including 0.43 Pg DIC and 0.17 Pg PIC (Probst et al., 1994). However, total atmospheric carbon (TAC = DOC + soil POC + riverine atm. DIC) flux transported to oceans were estimated to 542 $Tg.Yr^{-1}$ of which 37% as DOC, 18% as soil POC and 45% as DIC (Meybeck, 1993); and then 46 % of TAC flux originates mostly from humid tropics followed by temperate forest and grassland (31%). The riverine carbon flux exported by African rivers is estimated to about 25.03 $Tg.Yr^{-1}$ for DOC, 34.56 $Tg.Yr^{-1}$ for POC, and 41.10 $Tg.Yr^{-1}$ for POC (Li et al., 2017). Their total riverine carbon flux (DOC+POC+DIC) represents 11.30% of the world's riverine carbon flux transported to the ocean, which ranks African rivers and the European ones (7.07%) the less carbon providers to the oceans (Li et al., 2017). Asia (29. 34%), North America (21.52%), South America (18.36%) are preceding Africa and Europe continents in terms of riverine carbon flux. For COD, the Ogooué basin contributes to approximately 0.35 % of world riverine flux exported to the oceans every year. This estimation is made according to water discharge value (Q = 150 km^3/yr) and COD concentrations (5.1 ± 1.9 mg/l) obtained on Ogooué watershed (Li et al., 2017). Then Ogooué watershed exports yearly (0,8 ± 0.3) 10^{-3}Pg of COD to the ocean, which represents 3.2 % of the Africa continent riverine COD exportation (25.03 $Tg.Yr^{-1}$). The minimal and maximum exportation COD flux of Ogooué basin are approximately

0,24. 10^{-3} Pg. Yr^{-1} and 1,4. 10^{-3} Pg. Yr^{-1}, respectively.

7 Brief comparison of changes in the Ogooué and the Congo river basins

When the Congo and Ogooué rivers are invoked, we must keep in mind the difference in size of both river basins. Indeed, the Congo River has an annual average discharge of 41,000 m³/s and drains an area of more than 3.5 million km² (Laraque, 1998; Laraque et al., 2001) while the Ogooué River has a flow rate of about 4700 m³/s for a drained area of 223000 km². Thus, the discharge of the Congo is approximately 9 times greater than that of the Ogooué, while the Congo River Basin is almost 16 times greater than that of the Ogooué River. Despite this difference of scale, a comparative study of some of the key variables of these basins may be very useful. The Congo Basin is so large that all climate forcings in Central Africa affect this basin; it is thus the most representative of the current climatic variability in Central Africa. An analysis of the covariation of climate parameters of the Ogooué and Congo river basins could provide a better understanding of the ORB's response to the ongoing climate dynamics in the region.

The first feature of the two basins to be compared is rainfall thanks to SIEREM, which made it possible to obtain long-term data (1940-1999) of rainfall for the whole of Africa at 0.5° X 0.5° spatial resolution (Boyer et al., 2006). Rain is the crucial parameter for the regionalization of environmental conditions and climate (Javari, 2016). Its variation affects patterns of climate variability both spatially and temporally. More specifically, the Congo and Ogooué river basins are located in Central Africa, which is a region characterized by abundant rainfall. It is also a very heterogeneous region whose spatial and temporal variability are still poorly understood, despite major studies conducted in the area (Nicholson & Entekhabi, 1987; Todd & Washington, 2004; Balas et al., 2007; Pokam et al., 2012; Nicholson & Dezfuli, 2013; Dezfuli & Nicholson, 2013; Pokam et al., 2014; Hua et al., 2016; Fotso-Nguemo et al., 2017; Nicholson, 2018; Tamoffo et al., 2019; Fotso-Kamga et al., 2019).

Figure 12 shows the average annual rainfall over the Congo and Ogooué basins. It is obvious that the Ogooué basin receives more rainfall per unit area (yearly average of 1,865 mm) than the Congo basin (average of 1,425 mm), over the period 1940-1999. Clearly, the differences between the maximum and minimum precipitation levels in the Congo and Ogooué basins are very different. The ORB is mainly coastal and receives large amounts of precipitation due to the monsoon flow of the Atlantic Ocean (Mahé et al., 1990) while precipitation is very heterogeneous in the Congo Basin due to various local and distant forcings with varying influences from one part of the basin to another (Nicholson et al., 2018). The main factors influencing precipitation in the Congo Basin are the monsoon flow of the Atlantic Ocean, the SST of the ocean basins, mesoscale convective systems delineated by the seasonal migration of Easterly Jets from northern and southern Africa and orography (Balas et al., 2007; Dezfuli & Nicholson, 2013; Nicholson & Dezfuli, 2013; Alsdorf et al., 2016; Nicholson et al., 2018; Nicholson, 2018). The migration of rainfall across the basin is such that the wettest periods are December - March and July - October for the basin regions further south and north respectively (Kazadi & Kaoru, 1996; Alsdorf et al., 2016).

In order to compare recent changes in rainfall in the Congo and Ogooué basins, the annual averages and SAI for the two basins were calculated and presented in Figure 13. It is apparent that both the Congo Basin and the Ogooué Basin entered a dry period from the 1970s onwards (Nicholson et al., 2018). It is characterized by long dry periods that kept pace during the 1990s in the Congo Basin, unlike the ORB where heavy rainfall resumed as early as the 1990s. However, in the Congo Basin, droughts of great severity were rarely recorded, dry years remained very moderate with mild severity overall. The striking difference that needs to be noted is the wet period before the 1970s, with the ORB recording far more dry years than the Congo Basin (12 and 5 years for the ORB and the Congo river basin respectively). In addition, the drought events recorded on the ORB are more severe than those in the Congo Basin (the ORB recorded a severe drought in 1958). Moreover, during the wet period (1940 - 1970), the ORB records short dry trends shown by the 5-year exponential moving average SAI while the Congo Basin does not. In contrast, the Congo Basin shows almost a total drought trend after the 1970s (Nicholson et al., 2018; Cartier, 2019). The dry trend observed in both basins after the 1970s is a regional phenomenon in Central Africa that differs from the droughts recorded in the Sahel by its mild severity (Mahe et al., 2001; Conway et al., 2009). In fact, although the exact causes remain poorly understood, the general diagnostic points out a trend towards drought in western equatorial Africa, particularly in the north of the equator (Mahe et al., 2001; Nicholson et al., 2018). Extreme precipitation has also decreased considerably (Aguilar et al., 2009). Moreover, in this regional trend, the coastal area is more impacted (Mahe et al., 2001), resulting in a more severe drought in the ORB, which is essentially a coastal area in contrast to the Congo Basin.

Hydroclimatic changes are not limited to precipitation, it is important to take into account other components of the hydrological cycle. For example, the variation in surface water volumes is an important indication of hydrological drought that better describes the drought severity, beyond the simple rainfall deficit. The standardized average annual discharges of the Congo river at Kinshasa (1903 - 2018) and the Ogooué river at Lambaréné (1930 - 2017) are presented in Figure 14 (data of the Congo river discharge are available in Laraque (1998)). For Congo, which has the longest series, there are three phases of evolution: a stable phase in 1930-1950 which the annual modulus hardly differs from the century average, a second, so-called wet phase marked by an impressive increase of the annual river discharges between 1950-1970 and the dry phase which is characterized by a long term significant decrease of the annual discharges which began as early as the 1980s (Laraque, 1998; Laraque et al., 2001; De Wasseige et al., 2015; Tsalefac et al., 2015). Inversely, the variations of the Ogooué start by a phase of large discharges during the 1930s with often occurrences of drought that gradually decreases and moves to a long phase of drought from the 1970s. Before the 1970s, the variations in discharges of the Ogooué River and the Congo River seem very independent. In turn, the variations of the discharge of the two rivers are similar in the period 1957 - 2017. This suggests a similar evolution of the hydrological cycle in both basins and certainly the same drivers of changes. These deficits observed in the flow rates of the Congo and Ogooué rivers from the 1970s onwards highlight once again the long drought observed by many authors (Laraque, 1998; Laraque et al., 2001; Mahé et al., 2005; Lienou et al., 2008; Mahe et al., 2013; Nguimalet & Orange, 2019). Although, it should be noted that given the very large size and even diversity of the Congo Basin, the processes to which this basin is subject may go beyond climatology.

Despite some recent prominent studies on hydroclimatic changes in Central Africa that have highlighted this drought in some parts of the region (Laraque et al., 2001; Mahe et al., 2013; Zhou et al., 2014; Hua et al., 2016; Ndehedehe et al., 2018), this phenomenon remains poorly understood. The phases of flow variation as well as that of precipitation observed throughout the last century in the Congo Basin have lasted from one to several decades (Laraque et al., 2001; Ndehedehe et al., 2019). Over the Congo Basin during the last century, periods of excess or deficit discharge correspond to climatic oscillations (temperature, rainfall) almost ten years over the entire left bank of the Basin (Kazadi & Kaoru, 1996). For further investigation of the effects of these climatic oscillations, Figure 15 shows the average monthly discharges over the past decades. In a very similar way to Ogooué, the double discharge maxima of spring and autumn in Congo are almost equal during the wet period and differ significantly during the dry phase. In addition, Laraque (1998) has established that since the beginning of this dry phase in the Congo river basin, spatial and temporal variations in rainfall have varied from 2 to 8%, while those of flows sometimes reach 30%, especially for tributaries on the right bank of Congo, i.e. essentially in the north of the Equator, as observed in the Ogooué basin. The same mechanism of pure equatorial regime is changed by the northern equatorial regime and a change in precipitation distribution (decrease in boreal winter precipitation) described by Lienou et al (2008) over the Ogooué basin occurs in the north equatorial part of the Congo river basin. This has led to discharge declines of up to 30% of the Oubangui river at Bangui (main tributary of the right bank of the Congo, in the north of the Equator) (Orange et al., 1995; Orange et al., 1997; Wesselink et al., 1996; Laraque, 1998; Laraque et al., 2001; Nguimalet & Orange, 2019).

Briefly, the Congo and Ogooué basins are subject to a multi-scale regional dynamic (in West Equatorial Africa and West Africa) with high varied effects in space and time highlighted in many studies (Mahé et al., 1990; Mahé, 1993; Olivry et al., 1993; Olivry et al., 1998; Laraque et al., 2001; Mahé et al., 2005; Lienou et al., 2008; Mahe et al., 2013; Hua et al., 2016; Dezfuli, 2017; Nicholson et al., 2018; Ndehedehe et al., 2018). The compelling causes of its changes are as diverse as their manifestations in the region. Many studies have attributed them to variations in the SST of the nearby Atlantic Ocean and other global ocean basins (Nicholson & Entekhabi, 1987; Mahé et al., 1990; Mahé & Citeau, 1993; Balas et al., 2007; Nicholson & Dezfuli, 2013; Dezfuli & Nicholson, 2013; Lutz et al., 2015), the intensity of the zonal equatorial circulation (Dezfuli et al., 2015; Hua et al., 2016), the Atlantic multi-decadal oscillation (Diem et al., 2014;

Martin & Thorncroft, 2014), the Madden-Julian oscillation associated with atmospheric dynamics (Berhane et al., 2015; Zaitchik, 2017), El Niño Southern Oscillation (ENSO) in relation to global circulation (Balas et al., 2007; Maloba Makanga, 2015; Ndehedehe et al., 2018; Ndehedehe et al., 2019; Dezfuli, 2017), North Atlantic Oscillation (NAO) (Todd & Washington, 2004). However, in all these studies, no general consensus has been found to explain rainfall variability over Central Africa due to the diversity of both the forcings present and their effects in space and time (Nicholson et al., 2018). Even the meridian transit of the ITCZ, historically (and until very recently) used to explain the bimodal patterns of precipitations in equatorial Africa, is currently put into question (Nicholson, 2018). In general, to understand climate variations in Central Africa, the limit is probably not methodological in view of everything that has already been done, but the lack of reliable data. Although hydrometeorological measurements began in this region at the end of the 19th century, it was mainly between 1950 and 1980 that the monitoring was carried out (Nicholson et al., 2012). Because since the 1980s, most of the stations have been not operating. Fortunately, there is a new window of opportunity with the synergy of multi-satellite data and numerical modeling (Becker et al., 2014; Lee et al., 2011; Becker et al., 2018; Kim et al., 2017; Kim et al., 2017; Kittel et al., 2018; Bogning et al., 2018a; Kim et al., 2019; Alsdorf et al., 2016; Fotso-Nguemo et al., 2017; Fotso-Kamga et al., 2019).

8 Past and future monitoring of the Ogooué river basins

In 1856, the French explorer Du Chaillu first spoke of a large river that was invisible on the maps and that he called Ogabai. This word pronounced Ogôûé in Mpongwe, means "great river" (Haug, 1903). Thus, the Ogooué River was inventoried and monitored at its downstream part at the end of the 19th century by many explorers who followed the great waterway and recognized some lakes and hypothesized the existence of other lakes and rivers through which the lake basins were linked to the river basin. In 1866, the Englishman Walker founded the first factory in Lambaréné and contributed greatly to the knowledge of this part of the river. Between 1867 and 1887, several French naval missions carried out surveys along the Ogooué River from its mouth to Lambaréné and the gathered data have been used to draw up the first maritim maps of this region (Haug, 1903). This monitoring will be strengthened over the years and even more so within the basin. In the 1960s, the ORB had about forty hydrometric stations, which made it possible to provide water specialists with an already considerable amount of quantified information, published in the form of hydrological yearbooks. This inventory work has made it possible to provide a number of answers to engineers for the purpose of exploiting the basin (Carré, 1978).

However, after independence in Africa in the 1960s, the capabilities of monitoring of hydrological networks slightly decreased as young African governments were unable to afford the operation costs of such networks, which led to the stop of many stations (Carré, 1978). In the 1980s, no more stations were operating in the ORB. Unfortunately, the scenario is not limited to the ORB; in all major African basins, there has been a drastic reduction in monitoring networks during the first decades after independence. However, the exploitation of natural resources in the region has been forced to strengthen to enable local governments to ensure economic and infrastructural development for the benefit of their populations. These exploitations have contributed significantly to the anthropization of local ecosystems to the extent that they have been identified in some studies as partly responsible for some of the observed changes (Mahe et al., 2013). However, the ORB has benefited from an exceptional conservation policy in the region. Indeed, unlike the rest of the humid forests of Central Africa, which is highly anthropized, Gabon's ecosystems, including the ORB, have remained almost intact thanks to a very good locally administered conservation policy (Fichet et al. 2014; Sannier et al. 2014; Braun et al., 2015).

However, the Gabonese authorities have recently launched ambitious projects to exploit national natural resources, develop agriculture and build infrastructure that could significantly disrupt the long-standing harmony between people and environment. In addition, the lack of reliable measurements due to the discontinuation of monitoring networks could lead to disproportionate exploitation of local natural resources or inappropriate infrastructural developments causing de facto degradation and exacerbation of local ecosystems. In addition, the ongoing changes in the ORB mentioned above do not augur well for the future. Regional climate models predict an increase in water resource depletion in Central Africa in most scenarios (Malhi & Wright, 2004; Tsalefac et al., 2015; Fotso-Nguemo et al., 2017; Mba et al., 2018).

Nevertheless, these development projections are accompanied by a government commitment to establish a serious partnership with scientists to obtain accurate information to understand the evolution of local ecosystems in order to determine the least devastating exploitation approaches (Gambotti, 2014). To meet the institutional and scientific issues related to the management of the resources of this basin, an observatory of the critical zone of the Ogooué basin is being set up. It is carried out by the Gabonese government agency for the protection of nature, the “Agence Nationale des Parcs Nationaux du Gabon” (ANPN) and its scientific partners: the “Institut de Recherche pour le Développement” (IRD) and the Programme Pluridisciplinaire Régional "Changements Globaux, biodiversité et santé en zones forestières d'Afrique Centrale" (PPR FTH-AC) and finally the American non-governmental organization “The Nature Conservancy” (TNC) with its “Great River Project” including the Ogooué River. The observatory of the

Ogooué River critical zone (CZO) is innovative in the sub-region, which is almost entirely devoid of it, with the notable exception of the Nyong basin in southern Cameroon. Short to mid-term scientific questions of the CZO include (Braun et al., 2015): (i) Water cycle: Combining high frequency in situ parameters with multi-satellite data (e.g. altimetry); (ii) Biogeochemical cycles: Carbon & nutriments fluxes, GHG emissions,…; (iii) Weathering/erosion: saprolite production versus soil breakdown with ∂^7Li, CRN, contemporary biogeochemical fluxes…; (iv) Biosphere and forest dynamics: Lidar, multi-satellite data, ground measurements … and (v) Ecological functions and ecosystem services. In addition, TNC along with IRD is helping to gather fresh information about the volume, speed, and discharge of rivers, working alongside Gabon's Ministry of Energy, the Gabon Research Institute, and ANPN.

In a complementary way, multi-satellite data are used to compensate for the lack of in situ data on ORB and other Gabonese river basins. In 2010, Gabonese authorities set up their Agency for Space Studies and Observations (AGEOS) with many objectives including developing a national forest monitoring capacity. In addition, the European Space Agency has developed carbon stock monitoring activities in the Congo Basin through the REDD extension of its Global Monitoring for Environment and Security (GMES) Element on Forest Monitoring program (GSE\FM) (Häusler & Gomez, 2006). Numerous forest monitoring studies have already been carried out (Fichet et al., 2012; Sannier et al., 2014; Fichet et al., 2014; Sannier et al., 2016). Nevertheless, in order to reconstruct the hydrological variations of recent decades in the ORB, (Bogning et al., 2018a; Bogning et al., 2018b) used seven radar altimetry satellite missions (ERS-2, ENVISAT, Saral/Altika, Jason-2, Cryosat-2, Sentinel-3A, Jason-3) to derive water level variations at more than 30 reaches of the Ogooué River and its main tributaries and establish a reliable time series of discharge of the Ogooué to Lambaréné. The quality of altimetry-based water levels strongly improved with the use of the Ka-band (smaller footprint and higher bandwidth frequency compared to the Ku-band generally used on most of the radar altimetry missions (Bonnefeond et al., 2015)) onboard SARAL and of the Synthetic Aperture Radar (SAR) acquisition mode (smaller footprint along the track (Raney et al., 1998)). A combination of multi-satellite data has been successfully used to inform a model of large ungauged basins in the ORB (Kittel et al., 2018). In addition, the continuity of altimetry missions has already been planned with, for example, Sentinel-6/Jason-CS (Jason Continuity of Service) radar altimeter mission for ensuring the same (or better) level of performance as earlier altimetry missions owing to the use of the SAR acquisition mode. The ORB will also be monitored by the future wide-swath altimeter mission SWOT (Surface Water Ocean Topography) during its preliminary 1-day revisit phase. Nevertheless, in situ stations should not be neglected, as they are important for the calibration and the validation of satellite measurements. Fortunately, TNC in partnership with ANPN and IRD is planning to set up about ten of these stations in the river basins of Gabon, including in the ORB.

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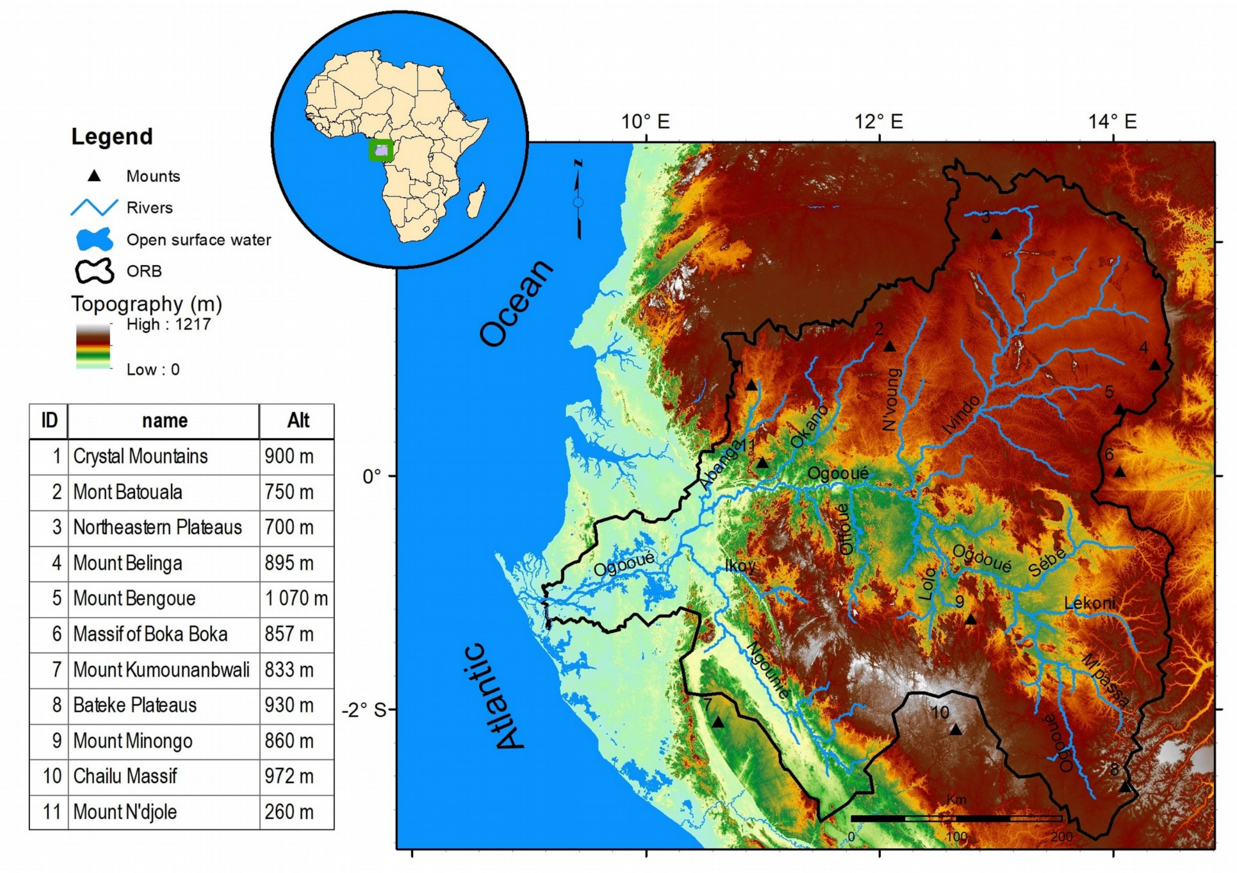
Table 1. Categorization of drought from SAI.

SAI	Drought Category
>2	Extreme wetness
From 1.5 to 2	Severe wetness
From 1 to 1.49	Moderate wetness
From 0 to 1	Mild wetness
From -0.99 to 0	Mild drought
From -1.49 to - 1	Moderate drought
From -1.99 to - 1.50	Severe drought
≤-2	Extreme drought

Table 2. Occurrence of wet and dry years in the ORB from 1940 to 1999.

Category	Zone 1	Zone 2	Zone 3
Extreme wetness	1	0	1
Severe wetness	0	2	1
Moderate wetness	3	4	3
Mild wetness	24	24	24
Mild drought	27	26	26
Moderate drought	3	1	3
Severe drought	2	2	1
Extreme drought	0	1	1

Figure 1. Portes de l’Okanda in the Lopé national park (Credit: R. Boss, 2005).



ID	name	Alt
1	Crystal Mountains	900 m
2	Mont Batouala	750 m
3	Northeastern Plateaus	700 m
4	Mount Belinga	895 m
5	Mount Bengoue	1 070 m
6	Massif of Boka Boka	857 m
7	Mount Kumounanbwali	833 m
8	Bateke Plateaus	930 m
9	Mount Minongo	860 m
10	Chailu Massif	972 m
11	Mount N'djole	260 m

Figure 2. Topography and hydrographic network of the ORB. Topography data are from ETOPO1 1 Arc-Minute Global Relief (Amante & Eakins 2009).

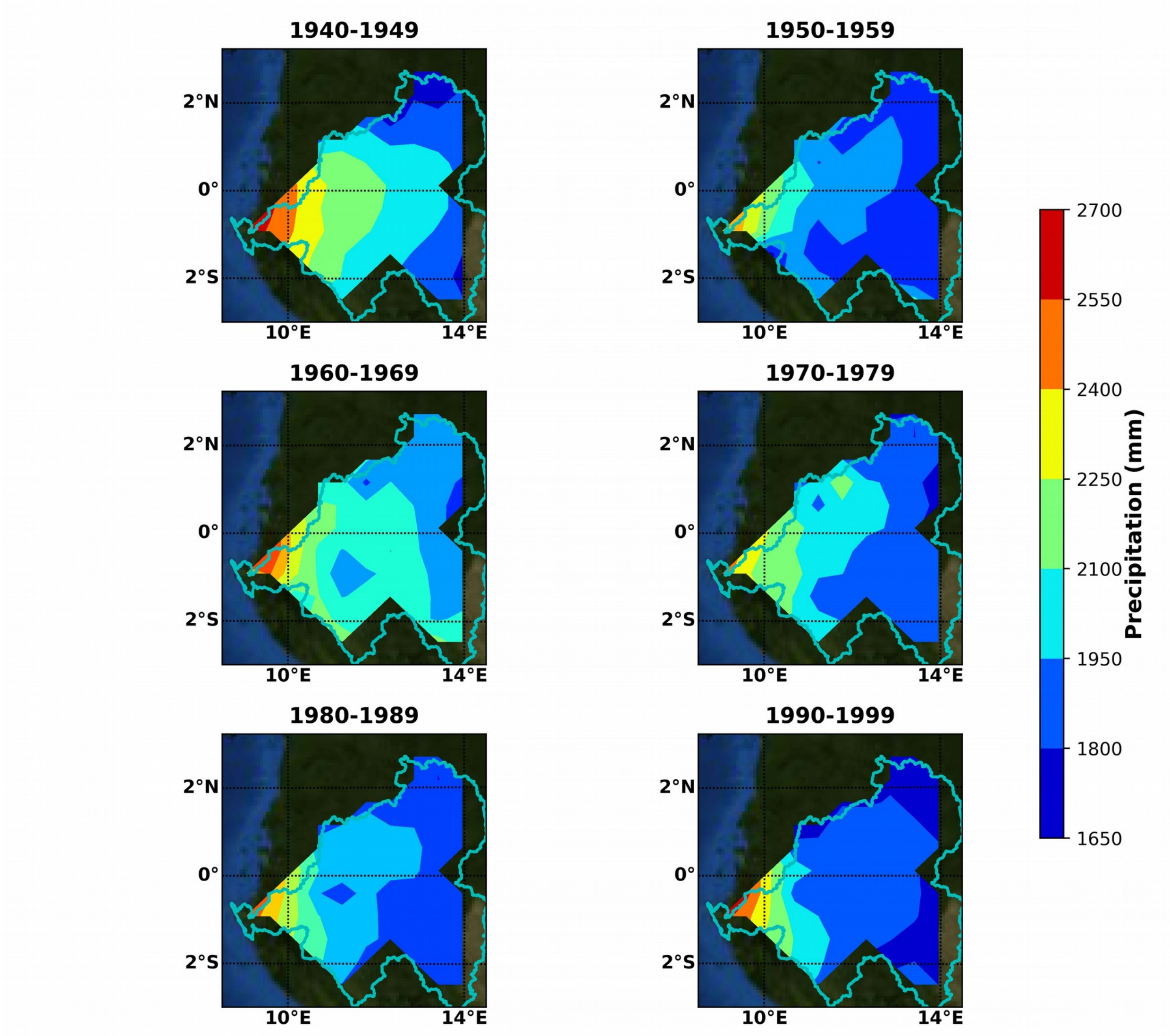


Figure 3. Annual average of rainfall in the ORB for the six decades observed during the period 1940-1999.

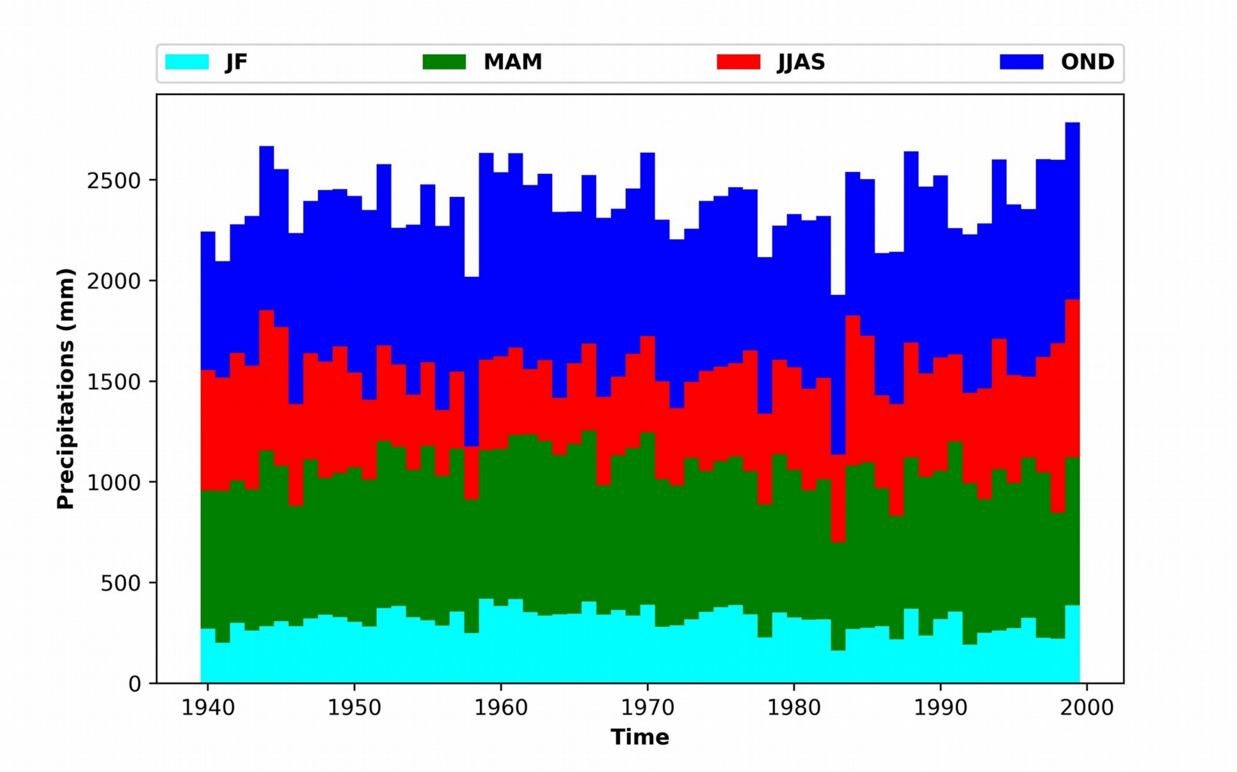


Figure 4. Time series of annual rainfall in the ORB (1940 - 1999). Annual rainfall is decomposed in seasons along the hydrological year (JF = January-February, MAM = March - April, JJAS = June - September and OND = October – December).

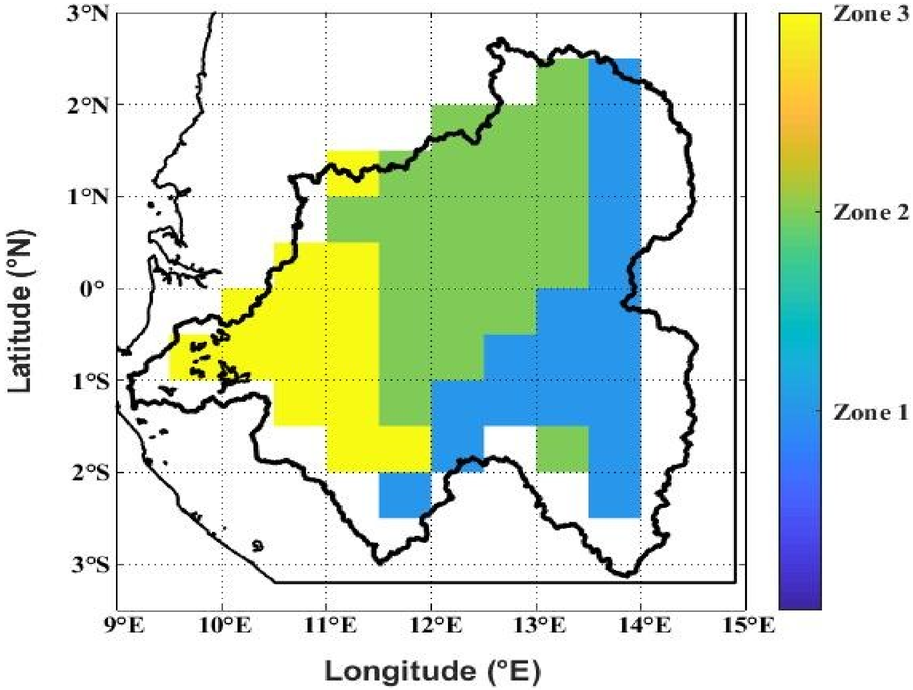


Figure 5. K-means delineation of homogeneous rainfall zones in the ORB based on SIEREM rainfall data.

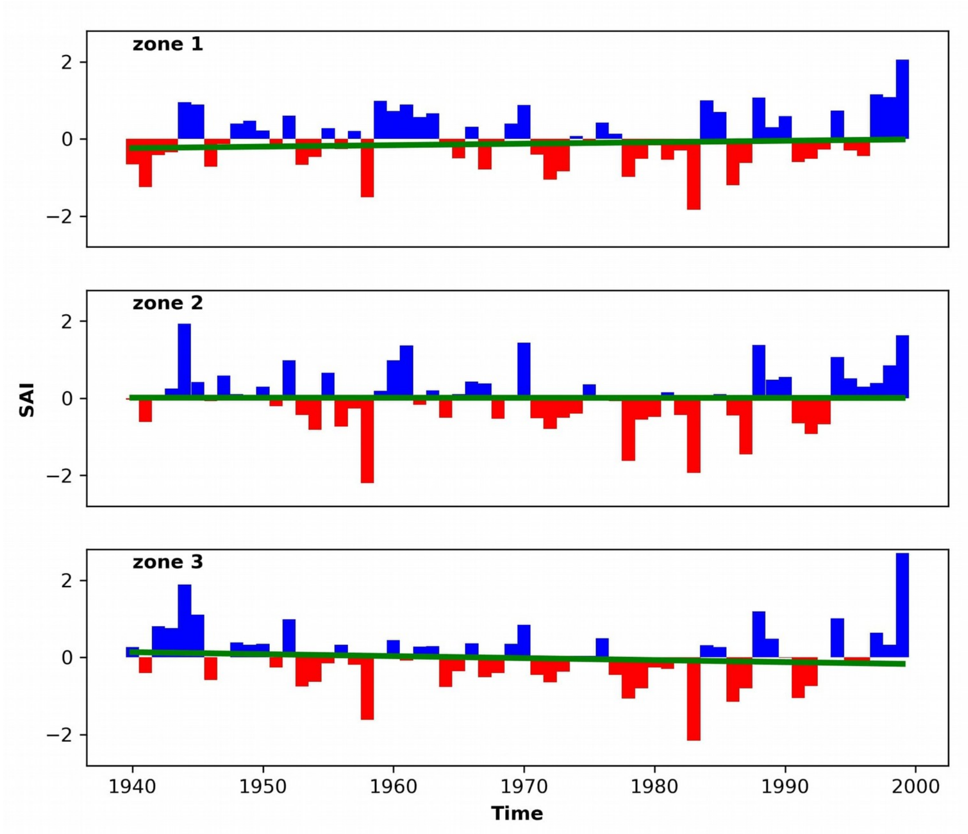


Figure 6. Temporal variations of the standardized anomaly index of rainfall between 1940 and 1999 over the ORB (barplot). The solid green lines are Sen's estimated trendline.

Figure 7. Fall of Kongou on the Ivindo (credit: Jean-Louis Albert 2010).

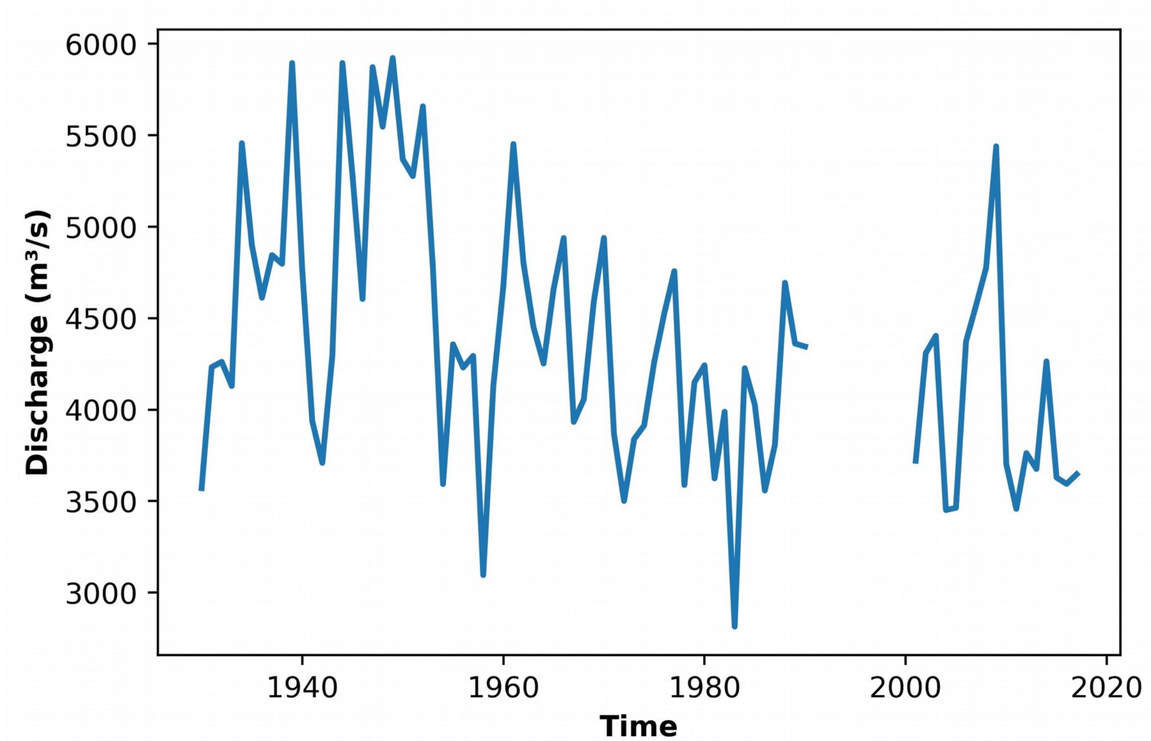


Figure 8. Annual variations of the Ogooué River discharge at Lambaréné gauge station from 1930 to 2017.

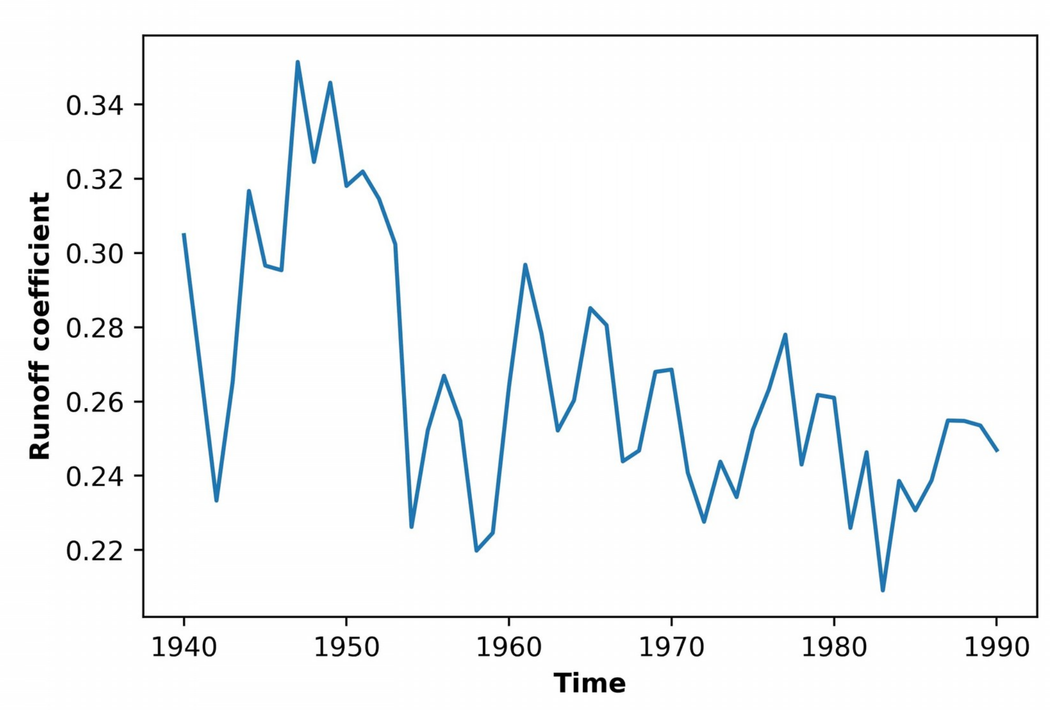


Figure 9. Runoff coefficient of the ORB (1940-1990).

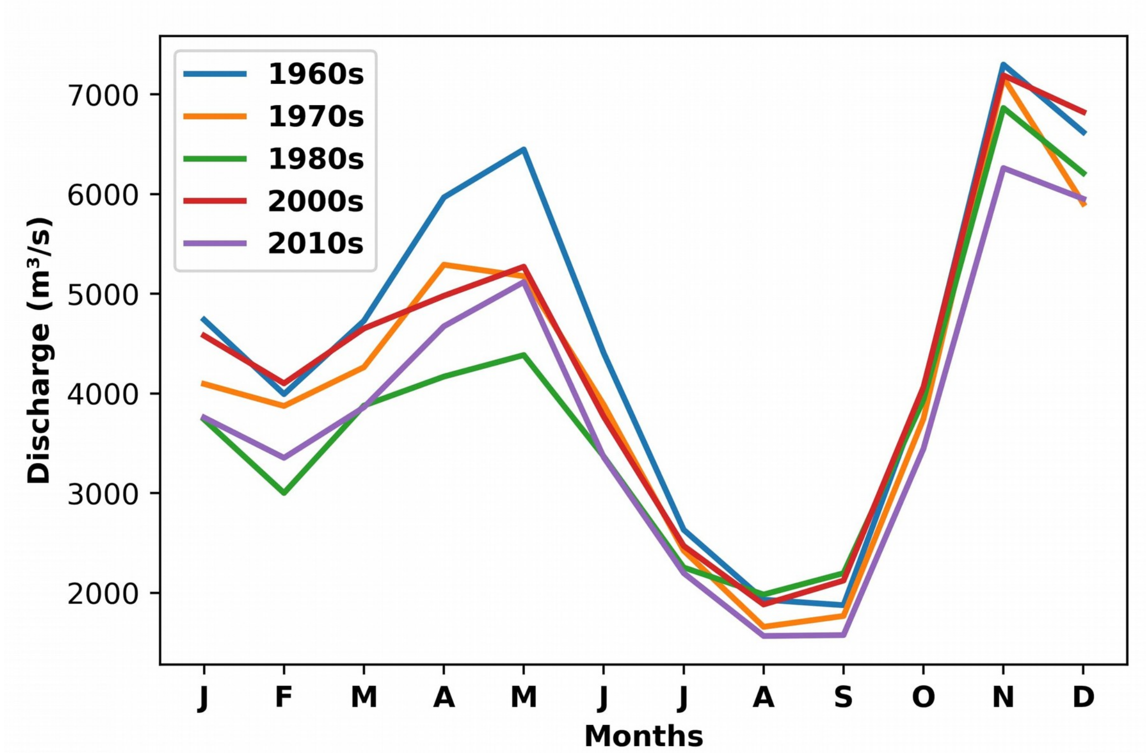


Figure 10. Hydrographs of the Ogooué River discharge for decades from the 1960s to the 2010s.

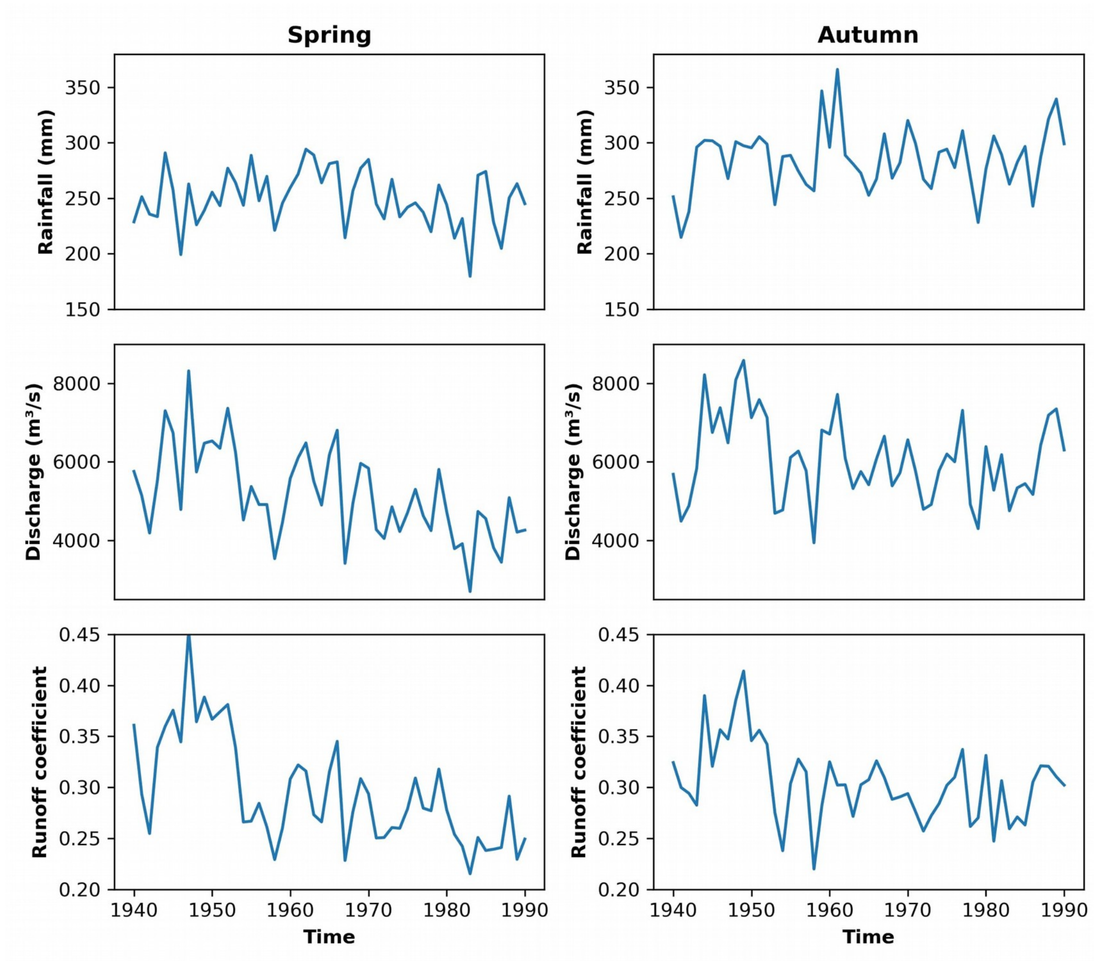


Figure 11. Interannual variations of rainfall, river discharge and runoff coefficient in the ORB.

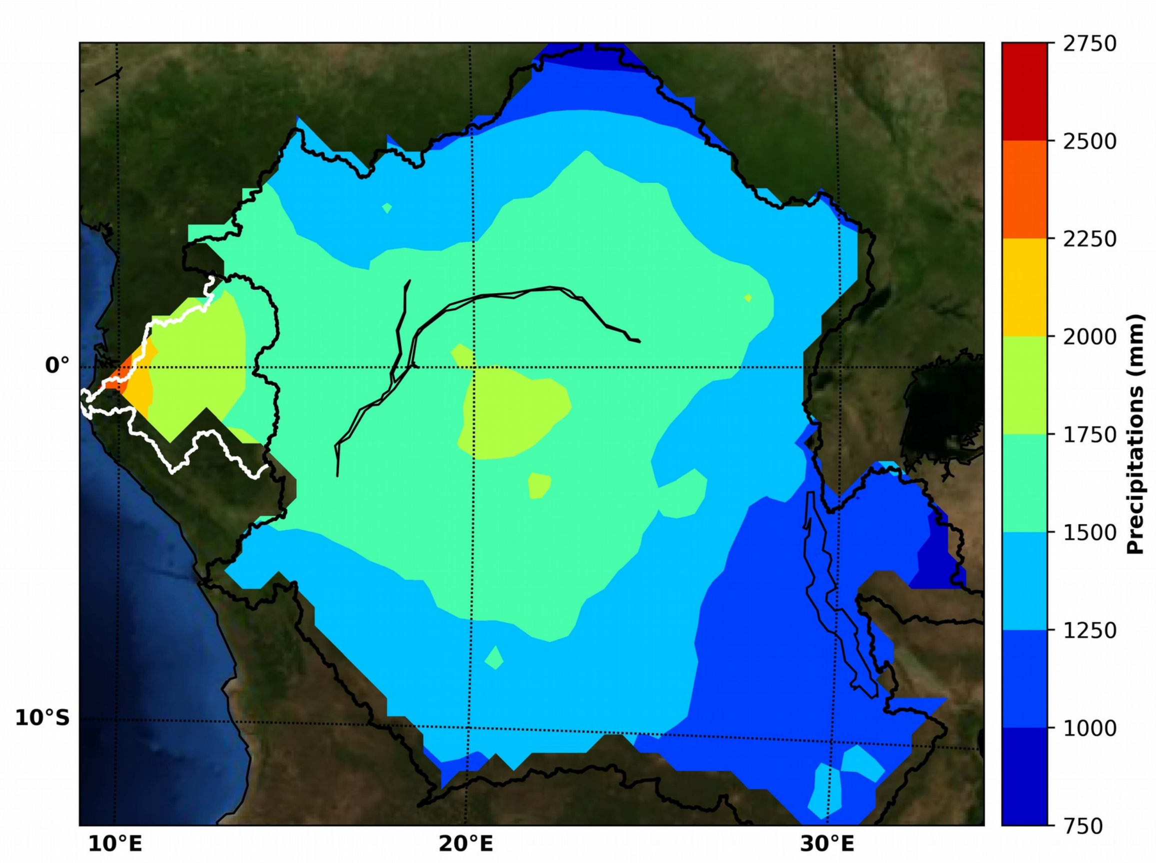


Figure 12. Mean annual rainfall from SIEREM in both Ogooué river (white boundary) et Congo river (black boundary) basins.

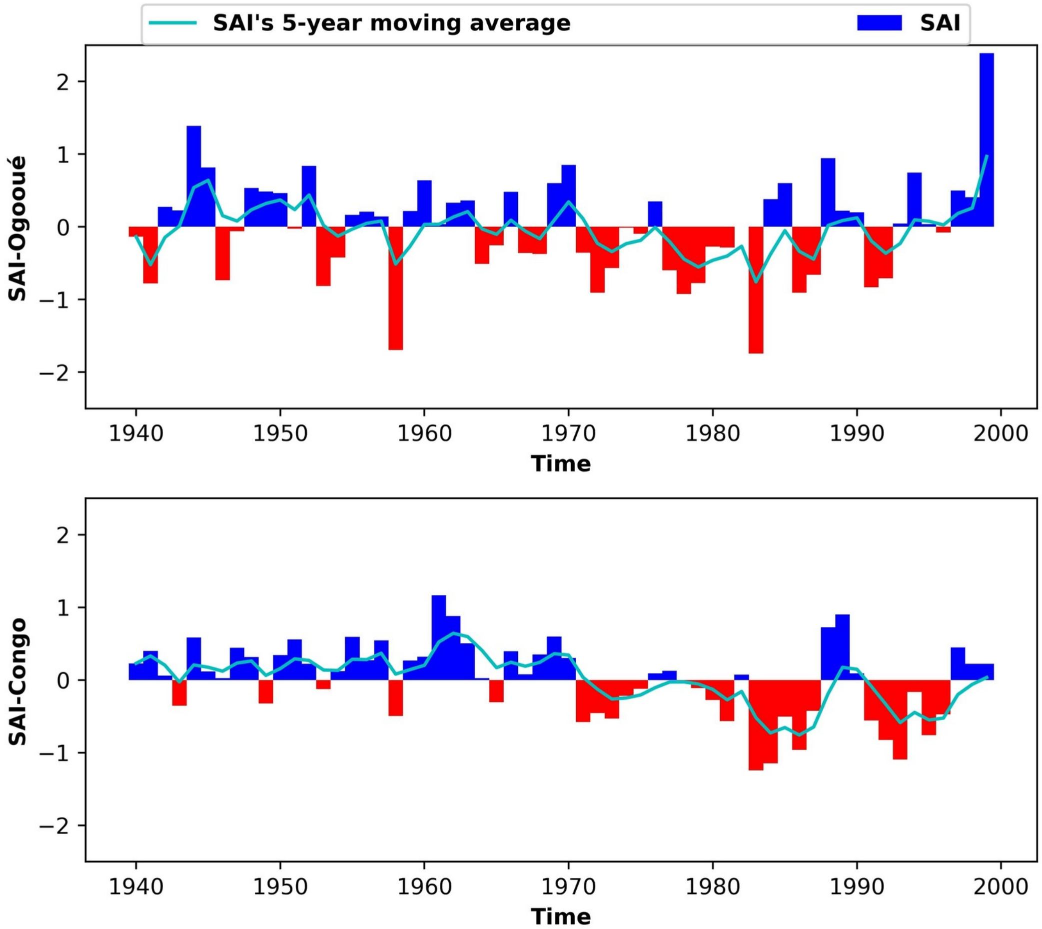


Figure 13. SAI of both Ogooué River et Congo River basins between 1940 and 1999 (upper and lower panels respectively). The trend of the standardized precipitation index between 1940 and 1999 is represented using a 5-years moving average (light green).

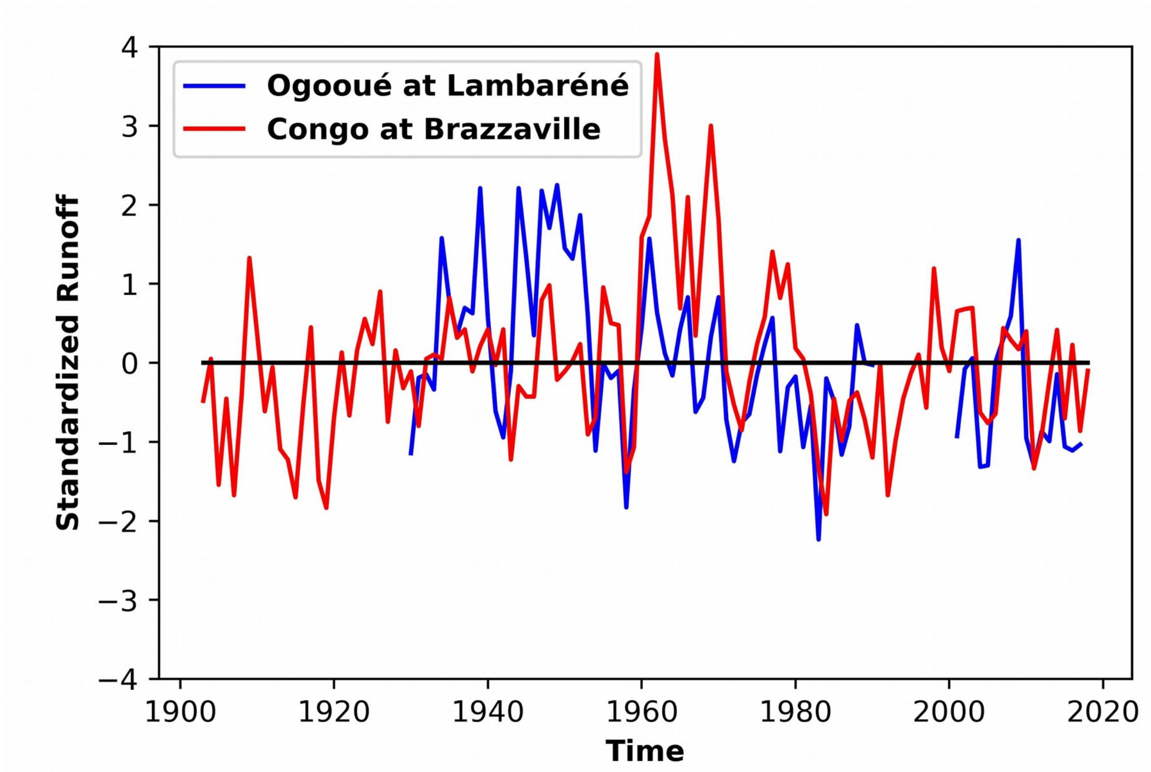


Figure 14. Standardized discharge anomalies for both Ogooué et Congo rivers.

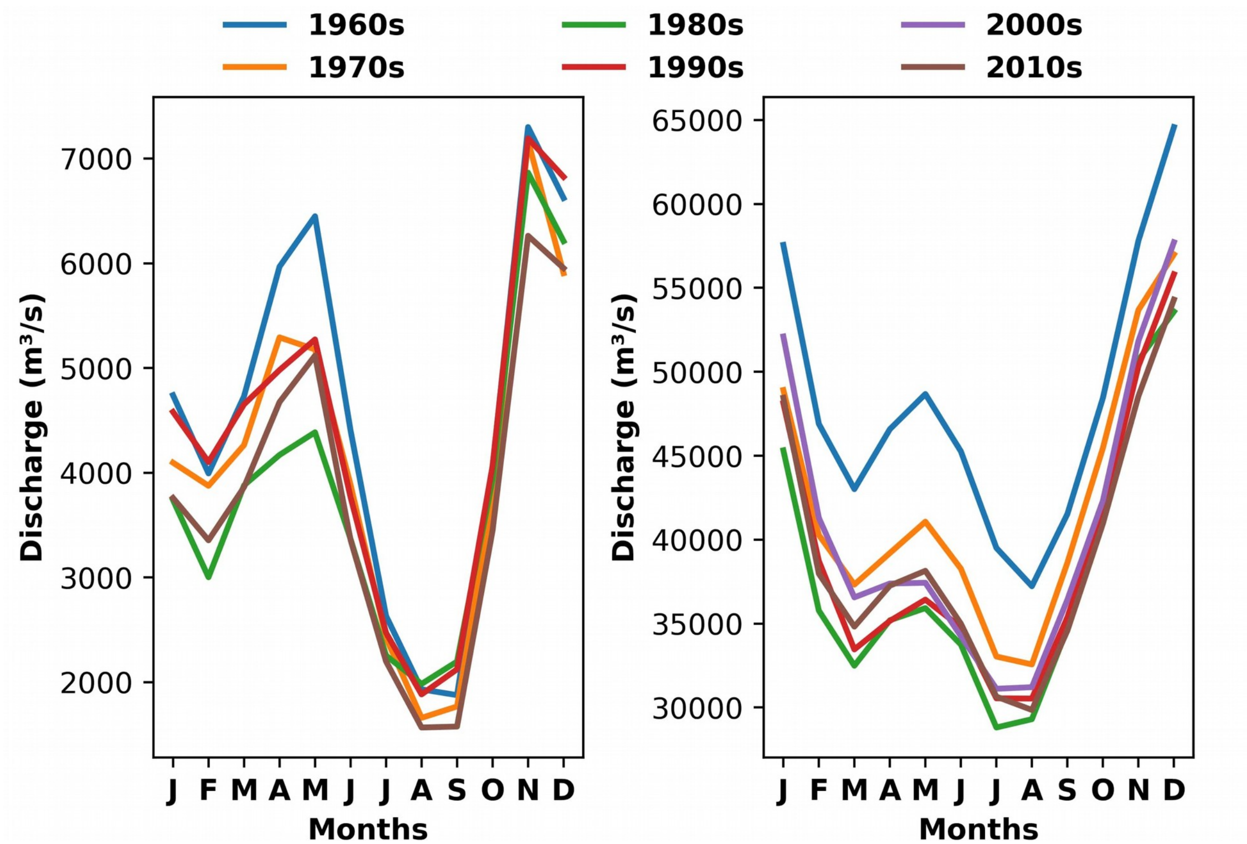


Figure 15. Hydrographs of the Ogooué river and the Congo river discharges for decades from the 1950s to the 1990s.