# I this document we included the Reponses to the Reviewers and a copy of the article with changes visible.

## Reviewer 1

Dear reviewer, thank you for your valued time dedicated to reviewing this paper. Your contributions certainly will improve it. Here you can find the response to your comments, questions, and suggestions. The paper will be submitted for a careful English editing.

### Comment 1:

This is quite and unique region. It comprises the second largest rainforest in the world, and while there have been so many studies analyzing the Amazon, the recycling rates in the Amazon are not nearly as large as the ones reported here. I think it is important to point this out. There are few regions in the world that have such high terrestrial sources of moisture and can sustain a rainforest!

### Response 1:

We are agreeing. We have improved in the introduction the section 1.1.

### 1.1    Region of Study

*The Congo River Basin (CRB) is located in central-equatorial Africa, an important part of the continent containing major rivers and dense forest (Fig. 1). With an approximate area of 3,687,000 km2 (Alsdorf et al., 2016), the basin includes several African countries: the Democratic Republic of the Congo (DRC), the People's Republic of the Congo, the Central African Republic, and parts of Zambia, Angola, Cameroon, and Tanzania (Chishugi, 2008). The Congo River (also known as the Zaire during at one time) is over 4,375 km long, considered to be the fifth longest river in the world, and the second longest in Africa after the Nile River (IBP, 2015). Its discharge shows a composite variability, which is due to the sum of its tributaries (Laraque 2001). With an annual discharge of 5000 m3 s-1 at its mouth, the Oubangui River is the second most important tributary to the Congo River (mean flow 41 000 m3 s-1), after the Kasai River (8000 m3 s-1) (Briquet, 1995).*

*The CRB comprises the second largest continuous rainforest in the world; covering an area of approximately 1.8 Million km2 the high rate of evaporation is comparable to the oceans is one of the main features of the forests, being extremely important for storing carbon and having an impact on the continental and global climate system mainly through the water cycle (Haensler et al., 2013; Marquant et al., 2015; Wasseige et al. 2015). The basin is composed basically of a central area that contains an immense forest swamp best known as "Cuvette Centrale"; an immense depression at the centre of the basin where sediment accumulation since the Quaternary alluvial deposits rest on thick sediments of continental origin, consisting principally of sands and sandstones (Kadima et al., 2011; Gana and Herbert, 2014) (Fig. 1). Here the spatial distribution of forested wetland types is controlled by topography and also by the time and the intensity of the submersion, making it the most extensive peatland complex in the tropics (Dargie et al., 2017). From a rainfall point of view, because of the topographic barrier around the "Cuvette Centrale", the Congolese central basin functions to a large extent as a closed system of precipitation, on-site evaporation, and precipitation (Robert, 1946; Sorre, 1948). Located in the heart of the dense Congolese equatorial forest is the Lake Telé, an immense elliptical body of water (3 m deep for a surface of 23 km2 and a maximum water storage evaluated to 55x106m3) where hydrological exchanges are almost exclusively vertical with very little lateral contribution from the surrounding swamp (Lareque et al., 1998). Furthermore, the basin contains several large, permanent open water lakes including Lake Tanganyika, the largest of the African rift lakes and the world's second largest by volume and depth (Coulter, 1991; Cohen et al., 1993).*

*Around the central basin, there is mainly a humid evergreen dense forest and to the north and south mosaics of mixed forest; woody savannahs savannas and savannas (Marquant et al., 2015). The current distributions of different forest types correlate strongly with annual rainfall and particularly with the length and severity of dry seasons (CARPE, 2005). The CRB moist forests are the continent's main forest resource, containing an extraordinary biodiversity (Ilumbe, 2006; SCBD-CAFC, 2009) that brings important economic benefits to approximately 60 million people living in local communities (Hugues, 2011; Marquant et al., 2015). Unfortunately, in the CRB the rate of deforestation varies from one country to another. Overall, the basin had a net deforestation rate of 0.09% between 1990 and 2000, compared with 0.17% between 2000 and 2005 (Tchatchou et al., 2015). In fact, the satellite data show a widespread decline in greenness in the northern Congolese forest over the past decade, which is generally consistent with decreases in rainfall, terrestrial water storage, and other related aspects (Potapov et al., 2012; Zhou et al., 2014; Hua et al., 2016) like hydrological regimes (Laraque et al., 2001; Laraque et al., 2013; Wesselink, 1996).*

*The air masses originating from three permanent anticyclones located to the north-west (Azores), south-west (St. Helena), and south-east (Mascarene) of the CRB converge along the Intertropical Convergence Zone (ITCZ), which separates the southerly low-level winds from the northerly winds, and the Inter-Oceanic Confluence Zone (IOCZ), separating the westerly from the easterly winds in the southern part of Africa (Samba and Nganga, 2012). In general two modes of circulation: circulation of Hadley and the Walker circulation control the movement of air masses and the climate in Central Africa, leading to moisture convergence not being uniform in the atmospheric column (Tsalefac et al., 2015, Pokam et al., 2012). Areas which are positively correlated with Congo convection are areas of the ascending arm of the Hadley cell (Matari, 2002), while the east-west oscillation of the Walker circulation cell modulates the moisture advection from the Atlantic Ocean and the upward motion over the CRB (Matari, 2002; Lau and Yang, 2002) .*

*The rainfall-generating mechanisms are controlled by a zone of shallow depression systems in the CRB (Samba and Nganga, 2012) as well as north-south ITCZ migration (Samba and Nganga, 2012; Alsdorf et al., 2016) together with Mesoscale Convective Systems (MCS) (Jackson et al., 2009) and the African Easterly Jet along with the typical circulation of the Hadley cell (Nicholson, 2009; Pokam et al., 2012; Haensler et al., 2013).*

## Comment 2.

Related to the above, you need to explain (in lay terms in the conclusions) how >80% of the moisture is of terrestrial origin. I am not saying this is wrong, but It is difficult to imagine the mechanism by which this is happening. The moisture initially has to come from the ocean: but how can it climatologically be of terrestrial origin? I am having a difficult time understanding the process.

## Response 1 & 2.

Thank you. The next explanation has been introduced in the text to clarify the second part of the Comment 1 and the comment 2

*"We analysed separately the percentage of moisture supplied from land-based and oceanic sources to the total moisture inflow to the CRB for the period 1980-2010. The results confirm that over the whole year near or more than the 80% of the total moisture contribution to the basin origins in land sources, highlighting that more than the 50% of the total comes from the CRB itself (Fig. 10). Evaporation as a source for precipitation over land depends on the availability of surface moisture, which in turn depends upon the disposition of precipitation once it hits the ground (Trenberth 1998). In fact, according to with Eltahir (1998) the soil moisture conditions over any large region should be associated with relatively large boundary layer moist static energy, which favours the occurrence of more rainfall. This hypothesis was also confirmed for West African monsoons by Zheng and Eltahir (1998). In this line van der Ent and Savenije (2011) quantified the spatial and temporal scale of moisture recycling, independent of the size and shape of the region; through this method they found that about the 70% of the precipitation in the center of the South American continent is of terrestrial origin like in many parts of Africa, but specifically in the CRB where occur a strong moisture feedback. For Central Equatorial Africa (CEA) Pokam et al. (2012) and Trenberth (1999) reported a recycling ratio (the fraction of rainfall coming from evapotranspiration and not from moisture advected to the target region) higher than obtained for the Amazon in studies of Eltahir and Bras (1994) and Burde et al., (2006). In the CRB, as already commented the role of forests is also fundamental as they sustain atmospheric moisture through evapotranspiration, which is of utmost importance for the region's water resources, specifically the evergreen forest region (Matsuyama et al., 1994; van der Ent and Savenije, 2011). The key role of continental moisture sources has been also documented for monsoonal wettest regions like the Western Mexico (Bosilovich et al., 2003; Domínguez et al., 2008), Sudamérica (Drumond et al., 2014; Keys et al., 2014) and the Indian region (Misra et al., 2012; Pathak et al., 2015)".*

## Comment 3.

The results for the extreme events are interesting. Again, this is the first time I see that periods of extreme rainfall are associated with higher recycling – I've never seen this in other regions of the world! I suggest the authors analyze another wet period to see if this result is reproducible. The results for extremes were not reported in the abstract – please include.

**Response 3.**

We apologize because we made an improper use of the word "recycling". To understand this mechanism and
10  explain better we performed a backward experiment from CRB and calculated the anomalies of (E-P)>0 and the VIMF for the same years. Please consider the changes in section: ***3.4 Moisture sources during severe dry and wet periods in the CRB***. We hope it clarifies the explanation and your concern.

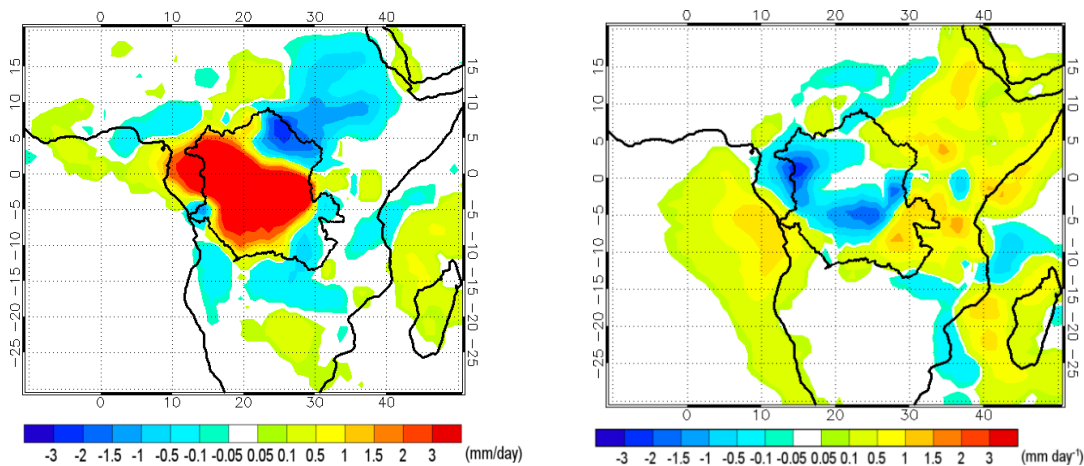
*During the period 1980-2010, the years 1995 and 1996 were characterized by severe (SPEI12_December = -1.69) and extreme*
15  *(SPEI12_December= -2.06) drought conditions respectively, while 1982 is characterized as severely wet (SPEI12_December = 1.68). Fig. 13 shows the mean annual contribution from all sources and the anomaly of |(E-P)i10<0| for each event. In 1982 (Fig.13a) the most important moisture contributions are from the basin itself (~120 mm day-1), O3 (~28 mm day-1), and C4 (~27 mm day-1). The anomalies of |(E-P)i10<0| from all the sources are positive, but it is particularly high for the basin itself (18 mm day-1). In 1995 and 1996 (Fig. 13b,c) the greatest moisture loss continues to be that from the air masses from the CRB itself, the oceanic source O3, and the continental C4. However, when*
20  *the anomalies were analysed all the sources showed negative values, meaning that the moisture support was, in fact, less than the average conditions for the whole period. In 1995 the deficit in the contribution from the CRB and O4 is highlighted. Hua et al. (2016) described how an increase in subsidence across the western edge of Indian Ocean (O4) and a decrease in convection over the Congo Basin (CRB) led to a reduction in moisture transport and rainfall across Central Equatorial Africa. In 1996, a year characterized by extreme drought conditions, the negative anomaly in the moisture supply from all the sources remains, but that computed for the basin is higher than it was in 1995. These*
25  *results explain a mechanism in which the CRB is more efficient providing moisture for precipitation over itself during wet (dry) periods increase (decrease).*
*To clarify these results, for the three years under study there was calculated the anomalies of |(E-P)i10<0| (moisture contribution) and (E-P)i10>0 (moisture uptake) in air masses tracked forward and backward in time, respectively, from the CRB. It worth noting that utilizing FLEXPART we obtained the budget of (E-P) but not exactly the recycling, which computes the amount of precipitation evaporated falling*
30  *again within the same region. Besides, to support the results there was calculated the anomaly of the Vertically Integrated Moisture Flux (VIMF) to check the dynamical conditions favourable to the convergence/divergence of moisture flux.*
*In 1982 a severely wet year, higher positive anomalies of |(E-P)i10<0| are observed in the half north of the CRB, but mostly negative in the south part (Fig. 14a). This pattern is clearly opposite to that obtained for the same year but in the anomalies of (E-P)i10>0 for the backward experiment (Fig. 14d), which explains the strengthening role of the half south of the basin as moisture source; mainly favouring the moisture*
35  *lose over the north part of the CRB, coinciding with the evergreen forest extends. The anomalies of the VIMF support this result, negative values identifying convergence are appreciated over the half north of the CRB, while positive anomalies indicating divergence in the half south (Fig. 15a). During a wet period is supposed that recycling decrease, however, for the Indian region Pathak et al. (2015) described that whereas the monsoon progresses the enhanced soil moisture and vegetation cover leads to increased evapotranspiration and recycled precipitation. Also for the North American Monsoon region, a positive feedback was previously described by Bosilovich et al. (2003), and*
40  *Domínguez et al. (2008). In 1982 it may happen that in the half north of the CRB increase both the evaporation and precipitation, but the second much more; thus, affecting the budget of (E-P). It was also documented when the tropical rainbelt shifts northward during boreal summer months; then, the evergreen forest gets active rapidly due to the onset of the rainy season, resulting in the increase of evapotranspiration (Matsuyama et al., 1994).*
*The Oubangui basin in the northeast of the CRB, should have benefited in 1982 due to positive anomalies of |(E-P)i10<0|, favouring the*
45  *precipitation in the half north of the CRB. In the Oubangui basin, a decrease in runoff observed everywhere coincides with a decrease in rainfall with a time lag of 3 years, which can be explained by the sponge-like functioning of the drainage basin, where interannual variability is less important for runoff than for the rainfall series (Orange et al., 1997). An important finding of theses authors is that also the maxima and minima of annual rainfall do not completely coincide with the extreme flow events; as occurred in 1982, a severely wet year when positive anomalies of |(E-P)i10<0| over the half north of the basin including the Oubangui basin. According to the results of Orange et al. (1997), it was*
50  *documented by Laraque et al. (2013) that from 1982 to 2010 the Oubangui remains in the drought phase, as the Congo returns to a phase of stability.*
*In 1995 a severely dry year, negative anomalies of |(E-P)i10<0| cover the major part of the basin (Fig. 14b) being more intense over the west and north. Over these areas in the backward analysis are observed positive anomalies of (E-P)i10>0 (Fig. 14e) and positive anomalies of the VIMF, indicating the prevalence of divergence (Fig. 15b). In 1996 an extremely dry year, the mechanism is the same like described for 1995*
55  *but negative anomalies of |(E-P)i10<0| occupy almost all the basin as well the positive anomalies of (E-P)i10>0 does. In the work of Trenberth and Guillemot (1996) are discussed the importance of land surface feedbacks in the 1988 drought and 1993 flood over the United Stated, while results of Dirmeyer and Brubaker, (1999); Bosilovich and Schubert (2001) and Domínguez, et al. (2006) agree that 1988 had a higher recycling ratio than 1993. To resume, in the CRB during dry years 1995 and 1996 prevail positive anomalies of (E-P)i10>0; indicating that moisture uptake by the atmosphere predominates. It surely occurs because the evapotranspiration is enhanced and precipitation decrease,*
60  *but the prevalence of divergence of the VIMF (Fig. 15b,c) does not favour the moisture lose over the basin, which must be transported*

*outside, suggesting the role of the CRB itself as a moisture source for remote regions. A more detailed analysis should be done in future works to determine the role of forests during drought conditions in the CRB. In Figure 12c it's possible to observe, that lowest SSI values obtained for the Kinshasa gauge station discharge data, occur after 1995 and 1996, as commented before due to the lag period from precipitation, runoff and underground water to feed rivers.*

5  *An important feature for 1982, 1995 and 1996 is that anomalies of moisture uptake and moisture contribution obtained in air masses tracked backward and forward in time, respectively from the CRB, are not homogenous over the CRB itself. In 1982 and 1995 is best appreciated a relocation of regions sources and sinks of moisture at the basin. This confirms that research on the hydrological cycle should not be developed for the entire basin as a whole, agreeing to Matsuyama et al. (1994). These authors argue that for the CRB the seasonal change of the water budget in the entire basin, can be recognized as the combination of those in the evergreen forest and southern deciduous forest*

10  *regions, but regional characteristics of the water budget in the basin cannot be explained by studying the basin as a whole.*

The results of extremes are now mentioned in the Abstract.

We made the same analysis for the second wettest year, 1988, and we found a similar result like in 1982. In the next figure is possible to observe positive anomalies of *|(E-P)i10<0| (left)* covering the center of the basin and extending southwest while the patter of *(E-P)i10>0 (right)* anomalies *is mostly opposite*.

20  Anomalies of *|(E-P)i10<0|* forward integrated from the CRB (left) and anomalies of *(E-P)i10>0* in a backward experiment. Moderate wet year (SPEI = 1.31) 1988.

## Comment 4.

In the description of the method, it is important for the authors to clearly write what the forward trajectories are providing for the analysis and what the backward trajectories are providing. It is my understanding that figures 9, 10, 11 can ONLY be obtained with the forward trajectories – is this correct?

30  ## Response 4:

Thank you for your suggestion. In the following text, we believe is more clear the purpose of use for the backward and forward analysis. It has been included in the text. Yes, you are right, figures 9, 10 and 11 were obtained from the forward analysis. It is mentioned at the beginning of the section: ***3.4 Moisture contribution from the***

35  ***sources. Forward analysis.***

*"The methodology implemented here is based on the Lagrangian model FLEXPART developed by Stohl and James (2004, 2005). The model allows us to track the parcels backward and forwards. The model outputs were*

*used to compute the gain and loss of humidity along trajectories of air particles leaving and arriving in the CRB. The backward analysis was utilized for the identification of the moisture sources for the CRB and the forward to obtain their climatological moisture supply and the relationship to the precipitation in".*

**Comment 5.**

In lines 15-27 of page 6, you need to understand the difference between streamflow and runoff. Streamflow includes baseflow (the contribution of groundwater) while runoff doesn't. It is not only the lag time because of the routing, but also the contribution of groundwater.

**Response 5.**

Thank you for clarifying the differences between these concepts. We have rewritten the paragraph like we reproduce below; in this, we changed the word streamflow by discharge and commented the groundwater influence:

*"The mean annual discharge of the Congo River is 38617.4 m3 s-1, as calculated from the GRDC monthly discharge values registered at the Kinshasa gauging station in the period 1980-2010. In the secular chronic of the hydro-pluviometric data (1903-2010) recorded at Brazzaville gauge station, close to Kinshasa and analysed by Lareque et al. (2013), the average flow of the Congo River from 1982 to 1994 is below the annual mean, followed by a period of stability from 1995 to 2010. At long-term results of Mahe et al. (2013) pose that as for the equatorial rivers, the Congo river runoff time series (at the Brazzaville station) follows no long-term trend (here these author refers runoff as discharge) and that the minimum shows a lesser inter-annual variability than that of the average or of the maximum.*

*The annual cycle of discharge (which is very similar to the precipitation and runoff) shows climatological maxima during November-December (Fig. 3) with values above 48000 m3/s, while in July and August the minimum is less than 30000 m3/s. Despite this, a difference is seen during March when high precipitation and runoff occur, but the discharge is low. During the next few months the precipitation and runoff decrease while in contrast the discharge increases, reaching a maximum in May. This lag should reflects the time needed for the surface runoff to reach the river mouth but also the groundwater contribution (Dai and Trenberth, 2002, 2008; Marengo, 2005; Rwetabula et al., 2007; Sear et al., 1999), as documented by Materia et al. (2012) using data recorded at Brazzaville station, about 400 km upstream of the river mouth. The direct relationship between precipitation over the basin and the discharge has a correlation of 0.52, which increases to 0.66 for a one-month lag (both statistically significant at p<0.05), confirming the lagged response mentioned earlier. Briquet, (1993) pointed out that a translation of the stability of this hydrological regime is shown by a high (low) frequency of floods occurrence on close dates from one year to the other. Future climate projections (21st century) despite to be uncertain, show a basin average increase in both rainfall and evaporation, but the total increase in rainfall tends to be higher than the increase in evaporation and result in most scenarios the runoff is increasing (Beyene et al., 2013). Nevertheless, for the northern sub-basins of the Oubangui and Sangha Rivers Tshimanga and Hughes (2012) downscaled scenarios in which occur more than 10% decrease in total runoff as a consequence of relatively little increase in rainfall and a consistent increase in potential evapotranspiration".*

**Comment 6:**

Line 15 of page 7: I think you mean east to west.

### Response 6:

You are right, thank you. The VIMF is from the east to the west. It has been corrected it in the paper.

### Comment 7:

The description of Figure 7 very poor. The analysis is not done in the order of the panels and it is very confusing, and I think including Figure 8 only makes it worse. The take-home message is that the contribution from each source can be completely different from the evaporation from each source. This highlights the importance of the atmospheric circulation in determining the contribution from a particular source. Please streamline this conclusion in the manuscript, make it much shorter, and I recommend deleting Fig 8.

### Response 7:

Thank you for your recommendations for this section. We have rewritten completely this section following your suggestions and deleted Fig 8 and his explanation. You can check it in the section:

### *3.3 Freshwater evaporation in the sources.*

*An analysis of the evaporation rate over the moisture sources may support our understanding of their role in the moisture uptake for the CRB over the year. It is most important to note that although the mean evaporation over a region considered to be a moisture source, quantified here using GLEAM and OAFLUX, can be high, its contribution to precipitation over the CRB might not be because it could be providing moisture for precipitation in other target regions as well. The geographical location of the basin allows it to receive moisture from the Atlantic and Indian Oceans, as well from land regions around the basin, as Fig. 6 shows. Oceanic evaporation is highly important if we consider that evaporation from the ocean surface equates to roughly 84% of the total amount of water evaporated from the planet (Oki, 2005), and the role of the oceans is decisive in continental precipitation (Gimeno et al., 2010). The mean annual evaporation from the sources is given in Table 1 using data from OAFlux and GLEAM for the ocean and continental regions, respectively. On average, O4 and O1 are the most evaporative sources while O3 is the least evaporative. Among the continental sources, the most evaporative are C2, CRB and C3.*

*Because the sources are located in two different hemispheres, they should have different annual evaporation cycles (Figure 7). From the FLEXPART backward experiment from the CRB, monthly positive values of $(E-P)i10$ were calculated over each source (hereafter E-FLEX) to compare over the year the average of evaporation over the sources with the moisture average uptake from each source to the CRB. $(E-P)>0$ can be discounted after $(E-P)$ has been integrated without altering the general patterns of net precipitation, where $(E-P)>0$ is discounted using a monthly or longer time scale (Castillo et al., 2014). In Figure 7 it is possible to observe both series for comparison, E-GLEAM (evaporation data over continental sources) or E-OAF (for oceanic ones) and E-FLEX. On the African continent, in C1 from May to October (boreal summer) E-GLEAM is higher than E-FLEX, and the opposite takes place in the other months, indicating when this source becomes more efficient in providing moisture to the CRB (gray shaded areas in Fig. 7, C1). The next continental source is C2 which shows the higher land annual evaporative value (Table 1). In this source, the annual cycle of E-GLEAM and E-FLEX differs from C1. Over this region, the E-FLEX values are greater than the local evaporation calculated using the GLEAM dataset during February and from June to October (gray shaded areas in Fig. 7, C2). Despite the local evaporation E-GLEAM does not show any great variations over the year, varying from 2 to 3 mm day-1, the E-FLEX shows a bimodal cycle with a minimum in May (~2 mm day-1) when major local evaporation occurs, and a maximum in August (~4.2 mm day-1) when local evaporation is at its lowest. This behaviour illustrates that it is possible to have moisture available in the atmosphere (higher E-GLEAM values) but less humidity is taken up by air masses and then carried towards our target region (lower values of E-FLEX); in this mechanism the rainfall over the region must play a key role since the E-FLEX could be lowest than E-GLEAM as a result of high P values over the region. The gray shaded areas in Figure 7 indicate those months when the transport of moisture is favoured from the source to the CRB. Over the course of several days an air parcel may undergo multiple cycles of evaporation and precipitation (Sodeman, 2008) and in our case, after integrating monthly data over 10 days it is hardly surprising that the E-FLEX values could be greater than local evaporation. Nevertheless, C2 is a land region, where the recycling concept is most useful because moisture for evaporation is limited by precipitation, whereas over the oceans the surface is clearly wet regardless of whether it rains or not (Trenberth, 1999). The C3 source, separated from C2 by the Congo River mouth, follows a similar annual evaporation cycle to C2, but with lower values (<1 mm day-1) during June-October (Fig. 7, C3). In addition, the E-FLEX values are higher than E-GLEAM in February and July-September. In the months of March-May and November, C3 becomes less efficient at providing moisture to the CRB. For the continental source C4, the annual cycle of*

*local evaporation (E-GLEAM) is similar to C2, C3 but the moisture uptake by air masses tracked backwards from the CRB (E-FLEX) over C4 is always greater than E-GLEAM (unless in February), indicating that this source is very efficient in terms of moisture uptake for the CRB, agreeing with results of van der Ent et al. (2014). For CRB the annual cycle of the E-GLEAM is characterized by maximum values during December-May and minimum in July-August (Fig. 7, CRB). In January-February, April-October, and December, E-FLEX is higher than E-GLEAM, in accordance with the decreasing precipitation over the basin (Fig. 3). This is understandable because the moisture uptake (E-FLEX) over the basin itself must be favoured when the precipitation over it decreases. Comparing the precipitation annual cycle in the CRB (Fig. 3) with E-GLEAM (Fig. 7), it can be seen that both show the same annual cycle, but they show opposite behaviour from E-FLEX (Fig. 7, CRB). This relationship describes a scheme in which the precipitation and evaporation are strongly lineally related; in fact, the evaporation as a source for precipitation over land depends on the availability of surface moisture, which in turn depends upon the disposition of precipitation once it hits the ground (Trenberth, 1999). But, the moisture uptake is the opposite, determining when the source is more effective in providing moisture for itself. This relationship is not strictly interdependent because it could be modulated by moisture income from the other sources or transported outside the boundaries of the target region (the basin).*

*Regarding the oceanic sources of moisture, in the source O1 the mean annual E-OAF is 4.60 mm day-1. This source is located on the Red Sea, where the oceanic evaporation rate is the highest in the world according to Abdulaziz (2012). After reviewing many studies Sofianos et al. (2002) confirmed several differences in the mean annual evaporation rate for the Red Sea, but it was estimated at around 2.06 m year-1 (~5.6 mm day-1). Figure 7 shows the annual cycle of evaporation (E-OAF) in this source, which is characterised by higher values during the boreal winter months and minimum values in summer, in accordance with Bower and Farrar (2015). Monthly E-FLEX values obtained over this source follow the same annual cycle as E-OAF but with lower values. This means that despite to be a high evaporative source, the moisture uptake from O1 to the air masses in transit to the CRB is less than that which it must provide itself to the atmosphere; converting it into a region that is not efficient in terms of the moisture supply to the CRB. In contrast, it seems an important moisture source during December-February over continental areas to its Northeast and during June-August to the remote area of the Indian Peninsula (Gimeno et al., 2010). Located in the Arabian Sea, the O2 source shows two evaporation peaks during December-January and June, and two minima in April and September (Fig. 7). This cycle was also noted by Sadhuram and Kumar (1987), who showed that the maxima are related to strong winds, and the minima are a result of low wind speeds together with weak vapour pressure across the Arabian Sea. The moisture uptake over this source between April-October is almost insignificant, but the evaporation from OAFlux is greater, which means that this source is not efficient in delivering moisture to the CRB, because during these months it instead contributes to the Indian monsoon (Levine and Turner, 2012). In the Atlantic (O3) has the smallest monthly average evaporation rate among all the oceanic sources throughout the year (<1 mm day-1), showing a negligible annual cycle. Materia et al. (2012) determined that the evaporation rate from the ocean surface is lower due to the fact that part of this oceanic region is affected by the huge freshwater discharge of the Congo River, contributing to a decrease in Sea Surface Salinity (SSS) and Sea Surface Temperature (SST). Despite this, E-FLEX is greater than E-OAF except for during April and May, when the moisture uptake over this source is less than 1 mm day-1. The moisture uptake has two peaks, one in February and the other in September-October. The last oceanic source is O4, the most evaporative and characterized by a maximum average E-OAF in May-July (>5.5 mm day-1) and a minimum at the beginning and end of the year (Fig. 7, O4). This behaviour is in accordance with the results of Yu et al. (2007), who argued that the enhancement of evaporation occurs primarily during the hemispheric winter (defined as the mean of December–February for the northern hemisphere and June-August for the southern). The positive values of E-FLEX over this source (O4) are lower and quite different from the mean E-OAF during all months. This means that on average this source is not very efficient in supplying moisture to the CRB. The efficiency of a region, providing moisture for precipitation at a target area, depends on the amount of evaporated water that reaches it, and not just on the initial evaporation rate. In this mechanism, we must highlight the importance of the atmospheric circulation patterns in determining the water vapour transport, and also, that moisture uptake from each source can be completely different from the evaporation in it.*

## Comment 8:

Figure 10: I would just have two bars, one terrestrial and one oceanic. Then denote the part of the terrestrial bar with the CRB contribution.

## Response 8:

We are agreeing. The figure is now changed according to your suggestion.

## Comment 9:

Please show statistical significance for Table 3. It is not clear to me that this figure is important for the conclusions in the manuscript.

## Response 9.

Dear reviewer, this table shows the significant monthly correlation (p<0.05) between the precipitation from CRU, Runoff from ERA-Int, River discharge from the GRDC and evaporation from GLEAM or OAFLUX, and series of |*(E-P)i10<0*| forward-integrated using FLEXPART from the sources over the CRB, and with the total |(E-P)i10<0|

5    amount (T).

In the paper, we represented the percentage of moisture supply from each source to the CRB respect the total *(E-P)<0* income. Besides, with this table, our purpose is to determine the linear relationship between the moisture contribution from the sources and some steps of the hydrological cycle in the CRB. The next paragraph has been

10   improved in the article in order to clarify this analysis:

*"In order to analyse the joint linear temporal variability, table 3 shows the significant correlation values obtained between monthly series of evaporation, precipitation, runoff in the CRB, river discharge at Kinshasa gauge station and |(E-P)i10<0| from each source over the CRB and the total |(E-P)i10<0| from all the sources (T). All the*

15   *correlation coefficients are positive and statistically significant at 95%, with the exception of that obtained between |(E-P)i10<0| over the CRB from C2 with the evaporation in the basin and the Congo River discharge at Kinshasa gauge station. As expected, the correlation is greater with precipitation than evaporation as |(E-P)i10<0| may be associated with rainfall process over the CRB. In most of the cases, the initial correlation values with evaporation and those followed obtained with the rest of variables decrease as a consequence of the lagged*

20   *response of the hydrological system. This behaviour is best appreciated for the correlation with |(E-P)i10<0| over the CRB, obtained in the air masses tracked forward in time from the CRB itself and for the Total contribution. In the correlation values shown in Table 3, |(E-P)i10<0| are best correlated with discharge than with evaporation in the basin, unless for |(E-P)i10<0| obtained in air masses from O4".*

25   **Comment 10:**

Figure 13 doesn't work for me. What (E-P) are you analyzing, over the entire region? Over the CRB? I don't know what the point of this graph is.

30   **Response 10:**

In this figure, we use the total *(E-P)i10<0* over the CRB obtained in the forward track from all the sources. It represents the correlation between the total moisture loss over the CRB and the SPEI at different time scales. Also with the runoff and the river discharge at Kinshasa gauge station. This analysis was not done for

35   evaporation and precipitation because they are involved in the calculation of SPEI.

With this analysis, we pretend to identify the months and time scale of the SPEI best correlated with moisture loss. Please consider the text below that we introduced to improve this explanation.

40   *We calculated the monthly correlations between the anomalies of the total moisture influx to the basin |(E-P)i10<0| (summed from all the sources), runoff, and SSI for the 1- to 24- month SPEI time scales (Figure 12) in order to investigate any possible temporal relationships. The significance of the correlation threshold was set at p<0.05. The correlations between monthly values of |(E-P)i10<0| and SPEI show significant and high values for all months (Fig. 12a), recorded for short SPEI time scales. The relationship is positive and statistically significant*

45   *from January to March within the 24 SPEI time scales. During low rainfall climatological months in the basin, especially in June, July and August the correlations become lowest even negative after the SPEI-4.-5 time scales, and generally remain until the last. It indicates a negative feedback that may reflect the increased evapotranspiration modulating the SPEI. As the months advance and the period of less rain ends, the correlations increase being positive and significant during October - December from first SPEI temporal scales*

50   *until SPEI-10 approximately. In these months for major SPEI, temporal scales correlations become lowest, being*

*also negative as can be appreciated in Figure 12a. However, it changes for January and February when as commented was found positive correlations at all SPEI time scales. This approximately shows a lag of one month needed for the SPEI to reflect wet condition recovery in the CRB.*

*In Figure 12b the surface runoff seems to be strongly dependent on precipitation deficit for both shorter and*
5  *annual rainfall deficit. When the rainfall increases over the basin from July to December (Fig. 8), the correlations also increase. Here we observe the same relationship described before between $|(E-P)i10<0|$ and SPEI; but higher correlations were obtained. Correlations between SSI obtained with Kinshasa gauge station discharge and the SPEI (1–24 months) show that the evolution of hydrological conditions is consistent with the meteorological rainfall deficit state over the basin (Figure 12c). In particular, the strongest and most significant correlations were*
10  *found with SPEI-5 to -7 from January to May, being maximum in April; this suggests the most appropriate time scales to use when identifying the hydrological drought (according to the Congo River discharge at Kinshasa gauge station) in terms of its relationship with the SPEI computed for the whole CRB. From May to July when the precipitation and discharge are minima (Fig. 3) the correlation are negative at first SPEI temporal scales; suggesting a time response of two or three months to reflect SPEI changes at river discharge.*

# Reviewer 2.

Dear reviewer, thank you for your contributions, certainly will improve the paper. Here you can find the response
20  to your comments, questions, and suggestions. The paper will be submitted for a careful English editing.

### Comment 1.

Here are some questions/comments/input to improve/supply this document:

This paper can be supplemented by a better presentation of the physiographic characteristics of the catchment,
25  presenting, in particular, the specificities and originalities of the forest cover and mostly of the vast "Cuvette Centrale" which plays a decisive role in the exchanges with the atmosphere. This paper needs also to be enriched by a paragraph about the spatiotemporal variations of hydrological regimes inside the Congo basin, with particular attention on the Oubangui catchment. It is well known that the northern part of the basin, impact on the discharge cycle at Brazzaville/Kinshasa gauging station (you can complete with some appropriates references
30  thank the list added).

**Reply 1**: Thank you for your suggestion. In the article, the section 1.1, dedicated to mentioning some aspects of the region under study is now improved. For this new version, we followed your recommendations. We utilized the references provided to enrich the discussion along the paper. Please read section:

35  1.1 Region of Study

*The Congo River Basin (CRB) is located in central-equatorial Africa, an important part of the continent containing major rivers and dense forest (Fig. 1). With an approximate area of 3,687,000 km2 (Alsdorf et al., 2016), the basin includes several African countries: the Democratic Republic of the Congo (DRC), the People's Republic of the Congo, the Central African Republic, and parts of Zambia, Angola, Cameroon, and Tanzania (Chishugi, 2008). The Congo River (also known as the Zaire during at one time) is over 4,375 km long, considered to be the*
40  *fifth longest river in the world, and the second longest in Africa after the Nile River (IBP, 2015). Its discharge shows a composite variability, which is due to the sum of its tributaries (Laraque 2001). With an annual discharge of 5000 m3 s-1 at its mouth, the Oubangui River is the second most important tributary to the Congo River (mean flow 41 000 m3 s-1), after the Kasai River (8000 m3 s-1) (Briquet, 1995).*

*The CRB comprises the second largest continuous rainforest in the world; covering an area of approximately 1.8 Million km2 the high rate of evaporation is comparable to the oceans is one of the main features of the forests, being extremely important for storing carbon and having*
45  *an impact on the continental and global climate system mainly through the water cycle (Haensler et al., 2013; Marquant et al., 2015;*

*Wasseige et al. 2015). The basin is composed basically of a central area that contains an immense forest swamp best known as "Cuvette Centrale"; an immense depression at the centre of the basin where sediment accumulation since the Quaternary alluvial deposits rest on thick sediments of continental origin, consisting principally of sands and sandstones (Kadima et al., 2011; Gana and Herbert, 2014) (Fig. 1). Here the spatial distribution of forested wetland types is controlled by topography and also by the time and the intensity of the submersion, making it the most extensive peatland complex in the tropics (Dargie et al., 2017). From a rainfall point of view, because of the topographic barrier around the "Cuvette Centrale", the Congolese central basin functions to a large extent as a closed system of precipitation, on-site evaporation, and precipitation (Robert, 1946; Sorre, 1948). Located in the heart of the dense Congolese equatorial forest is the Lake Telé, an immense elliptical body of water (3 m deep for a surface of 23 km2 and a maximum water storage evaluated to 55x106m3) where hydrological exchanges are almost exclusively vertical with very little lateral contribution from the surrounding swamp (Lareque et al., 1998). Furthermore, the basin contains several large, permanent open water lakes including Lake Tanganyika, the largest of the African rift lakes and the world's second largest by volume and depth (Coulter, 1991; Cohen et al., 1993).*

*Around the central basin, there is mainly a humid evergreen dense forest and to the north and south mosaics of mixed forest; woody savannahs savannas and savannas (Marquant et al., 2015). The current distributions of different forest types correlate strongly with annual rainfall and particularly with the length and severity of dry seasons (CARPE, 2005). The CRB moist forests are the continent's main forest resource, containing an extraordinary biodiversity (Ilumbe, 2006; SCBD-CAFC, 2009) that brings important economic benefits to approximately 60 million people living in local communities (Hugues, 2011; Marquant et al., 2015). Unfortunately, in the CRB the rate of deforestation varies from one country to another. Overall, the basin had a net deforestation rate of 0.09% between 1990 and 2000, compared with 0.17% between 2000 and 2005 (Tchatchou et al., 2015). In fact, the satellite data show a widespread decline in greenness in the northern Congolese forest over the past decade, which is generally consistent with decreases in rainfall, terrestrial water storage, and other related aspects (Potapov et al., 2012; Zhou et al., 2014; Hua et al., 2016) like hydrological regimes (Laraque et al., 2001; Laraque et al., 2013; Wesselink, 1996).*

*The air masses originating from three permanent anticyclones located to the north-west (Azores), south-west (St. Helena), and south-east (Mascarene) of the CRB converge along the Intertropical Convergence Zone (ITCZ), which separates the southerly low-level winds from the northerly winds, and the Inter-Oceanic Confluence Zone (IOCZ), separating the westerly from the easterly winds in the southern part of Africa (Samba and Nganga, 2012). In general two modes of circulation: circulation of Hadley and the Walker circulation control the movement of air masses and the climate in Central Africa, leading to moisture convergence not being uniform in the atmospheric column (Tsalefac et al., 2015, Pokam et al., 2012). Areas which are positively correlated with Congo convection are areas of the ascending arm of the Hadley cell (Matari, 2002), while the east-west oscillation of the Walker circulation cell modulates the moisture advection from the Atlantic Ocean and the upward motion over the CRB (Matari, 2002; Lau and Yang, 2002).*

*The rainfall-generating mechanisms are controlled by a zone of shallow depression systems in the CRB (Samba and Nganga, 2012) as well as north-south ITCZ migration (Samba and Nganga, 2012; Alsdorf et al., 2016) together with Mesoscale Convective Systems (MCS) (Jackson et al., 2009) and the African Easterly Jet along with the typical circulation of the Hadley cell (Nicholson, 2009; Pokam et al., 2012; Haensler et al., 2013).*

**Comment 2**

-Pa. 1 - Lig. 22: change "local evaporation or transpiration" by "local evaporation and/or transpiration"

**Reply 2**: Thank you. It has been changed.

**Comment 3**

-Pa. 2 - Lig. 28: change (also known as the Zaire) by (also known as the Zaire during at one time)

**Reply 3:** Thank you. It has been changed.

**Comment 4**

-Pa. 3 - Lig. 33: complete "Nevertheless, satellite data show a widespread decline in greenness in the northern Congolese forest over the past decade, which is generally consistent with decreases in rainfall, terrestrial water storage, and other related aspects (Zhou et al., 2014) by,

5 *"Nevertheless, satellite data show a widespread decline in greenness in the northern Congolese forest over the past decade, which is generally consistent with decreases in rainfall, terrestrial water storage, and other related aspects (Zhou et al., 2014, please complete with some others appropriates references in the list added), like hydrological regimes (please complete with some appropriates references in the list added)."*

10 **Reply 4:** Thank you. Please consider the next paragraph in which we have introduced the new appropriate reference from those provided by you. As figure 1 was changed the previous content of this paragraph too.

*"In fact, the satellite data show a widespread decline in greenness in the northern Congolese forest over the past decade, which is generally consistent with decreases in rainfall, terrestrial water storage, and other related*
15 *aspects (Potapov et al., 2012; Zhou et al., 2014; Hua et al., 2016) like hydrological regimes (Laraque et al., 2001; Laraque et al., 2013; Wesselink, 1996)".*

## Comment 5

Pa. 6 – "The mean annual discharge of the Congo River is 38617.4 m3 s-1, as calculated from the GRDC
20 monthly streamflow values registered at the Kinshasa-Brazzaville gauging station" here, it is necessary to specify during the 1980-2010 study period). Explain why the choose of this period and what about its representativeness on the entire secular chronic of hydro-pluviometric data?

## Reply 5:

We have introduced the next sentences in Material and Methods to explain the selection of the period 1980-2010.

*"The selection of global datasets was decided because of documented gaps in the hydrological information of the CRB (Tshimanga, 2012). However, observational data series are available on the SIEREM website (Boyer et al.,*
30 *2006) mainly to the north part of the basin. In this work, the analysis covers the period 1980-2010 taking into account the availability of ERA-Interim from 1980 and the river discharge data available at Kinshasa gauge station until 2010".*

35 *"The mean annual discharge of the Congo River is 38617.4 m3 s-1, as calculated from the GRDC monthly discharge values registered at the Kinshasa gauging station in the period 1980-2010. In the secular chronic of the*

*hydro-pluviometric data (1903-2010) recorded at Brazzaville gauge station, close to Kinshasa and analysed by Lareque et al. (2013), the average flow of the Congo River from 1982 to 1994 is below the annual mean, followed by a period of stability from 1995 to 2010. At long-term results of Mahe et al. (2013) pose that as for the equatorial rivers, the Congo river runoff time series (at the Brazzaville station) follows no long-term trend (here these author refers runoff as discharge) and that the minimum shows a lesser inter-annual variability than that of the average or of the maximum".*

**Comment 6:**

- pa. 5 lig. 26: You can complete and illustrate your description of the evolution of the global change in the Congo basin, using the different studies and data base about the rainfall and hydrological regime during the last century (see references list added and the SIEREM and ORE-Hybam site) http://www.hydrosciences.fr/sierem/and www.ore-hybam.org

**Reply 6:**

Thank you for the list of references. Please consider the new changes in section:

### *3.1 Climatology: Rainfall and runoff over the basin and Congo River discharge*

*The annual cycle of precipitation over the CRB is depicted in Figure 2. The most notable feature of the monthly patterns is the latitudinal migration of the maximum precipitation throughout the year, which leads to different seasonal patterns over the territory (Bultot, 1971; Chishugi 2008). Based on previous results Mahe (1993) defined four great climatic zones over the Congo Basin: the North (Ubangi River Basin), where the influence of the North African continental air mass is prominent; the South (Kasai River Basin), which is influenced by South African air masses; the eastern and south-eastern parts of the basin (Lualaba River Upper Basin), which are influenced by the humid Indian Ocean air masses; and the Center-West, where the climate is controlled by the Atlantic Ocean. In fact, the evaluation of the impact of rainfall on various sectors and its distribution throughout the annual cycle may be as important as the total annual rainfall (Owiti and Zhu, 2012). During January, February, and March, the southern half receives more precipitation, while April is a transitional month with maximum rainfall in the west-central and northeast parts of the basin. From May to August the rainfall pattern appears homogeneous and reveals that the majority of the average precipitation occurs in the northern part, coinciding with the northward excursion of the ITCZ between February and August (Nicholson and Grist, 2003; Suzuki, 2011). From May to October, the northeast of the CRB receive the highest rainfall, favouring the Oubangui catchment, a right-bank tributary of the Congo River that drains at the Bangui gauge station an area of 488500 km2 (Runge and Nguimalet, 2005). In September the rainfall increases to the south affecting the centre of the basin, with the greatest extension in October. In November, the central and southwestern parts of the CRB receive more rainfall and during December there is also an extension to the southeast. The regime of precipitation over the CRB is clearly differentiated by a latitudinal oscillation of maximum accumulated values, in accordance with several studies reviewed by Alsdorf et al. (2016) and within an interannual variability higher in the north and south than in the central units of the basin (Mahe, 1993).*

*Monthly average precipitation for the whole basin shows an annual cycle with two maximum peaks during March-April and October-December, with values greater than 4.5 mm day-1, each accounting for 21% and 32.6% of the mean annual rainfall in the CRB, respectively (Fig. 3). During June and July, the average rainfall reaches its lowest level of around 2 mm day-1. This cycle is similar to that described by Washington et al. (2013), who compared the Congo rainfall climatology through several datasets obtained from reanalysis and ensemble*

*models. However, they argued that the maximum rainfall in the basin occurs from March to May and from September to November, while the minimum occurs in June-August. The differences in monthly average precipitation may be due to the areas used; they used a box region over equatorial west Africa while we use the CRB boundaries.*

5   *The mean annual cycle of runoff in the CRB (Fig. 3) follows the same annual cycle as rainfall although it is always lower, varying between maximum values of 3.0 and 3.5 mm day-1 during November-March and minimum values below 1.5 mm day-1 during July and August. The long-term distribution of precipitation and runoff over the African continent is almost the same (Siam et al., 2013), but the highest values of runoff are concentrated in the heart of the equatorial forest along the Middle Congo River branch (Alemaw, 2012), with these wetlands receiving the majority of their waters from upland runoff (Lee et al., 2011) and several large rivers draining into the Congo in this middle*

10  *section; the largest of these is the Ubangi, at the north of the Congo Basin (Harrison et al., 2014). The interannual correlation calculated between the two series (precipitation and runoff) over the CRB is high, r = 0.73 (significant at p<0.05) and r = 0.72 with a one-month lag. Fig. 3 shows that from March onwards the runoff reflects a one-month lag compared with precipitation. In general, in a steady state, the precipitation exceeds the evaporation (or evapotranspiration) over the land and the residual water runs off, resulting therefore in a continental freshwater discharge into the oceans (Dai and Trenberth, 2002). This also occurs in the CRB, where monthly values of precipitation minus the*

15  *actual evapotranspiration obtained from the GLEAM dataset seem to follow the same annual cycle as precipitation (Fig. 3). In June (P-E) has a negative value, which means that on average there is more evaporation in the basin than precipitation [as in Dai and Trenberth (2002) and Siam et al. (2013)].*

*The mean annual discharge of the Congo River is 38617.4 m3 s-1, as calculated from the GRDC monthly discharge values registered at the Kinshasa gauging station in the period 1980-2010. In the secular chronic of the hydro-pluviometric data (1903-2010) recorded at Brazzaville*

20  *gauge station, close to Kinshasa and analysed by Lareque et al. (2013), the average flow of the Congo River from 1982 to 1994 is below the annual mean, followed by a period of stability from 1995 to 2010. At long-term results of Mahe et al. (2013) pose that as for the equatorial rivers, the Congo river runoff time series (at the Brazzaville station) follows no long-term trend (here these author refers runoff as discharge) and that the minimum shows a lesser inter-annual variability than that of the average or of the maximum.*

*The annual cycle of discharge (which is very similar to the precipitation and runoff) shows climatological maxima during November-December*

25  *(Fig. 3) with values above 48000 m3/s, while in July and August the minimum is less than 30000 m3/s. Despite this, a difference is seen during March when high precipitation and runoff occur, but the discharge is low. During the next few months the precipitation and runoff decrease while in contrast the discharge increases, reaching a maximum in May. This lag should reflects the time needed for the surface runoff to reach the river mouth but also the groundwater contribution (Dai and Trenberth, 2002, 2008; Marengo, 2005; Rwetabula et al., 2007; Sear et al., 1999), as documented by Materia et al. (2012) using data recorded at Brazzaville station, about 400 km upstream of the river*

30  *mouth. The direct relationship between precipitation over the basin and the discharge has a correlation of 0.52, which increases to 0.66 for a one-month lag (both statistically significant at p<0.05), confirming the lagged response mentioned earlier. Briquet, (1993) pointed out that a translation of the stability of this hydrological regime is shown by a high (low) frequency of floods occurrence on close dates from one year to the other. Future climate projections (21st century) despite to be uncertain, show a basin average increase in both rainfall and evaporation, but the total increase in rainfall tends to be higher than the increase in evaporation and result in most scenarios the runoff is increasing*

35  *(Beyene et al., 2013). Nevertheless, for the northern sub-basins of the Oubangui and Sangha Rivers Tshimanga and Hughes (2012) downscaled scenarios in which occur more than 10% decrease in total runoff as a consequence of relatively little increase in rainfall and a consistent increase in potential evapotranspiration.*

**Comment 7:**

In § 3.1and Fig. 2: why do you not used the monthly in situ rainfall data in the Congo Basin available during one century on the link (https://www.researchgate.net/publication/312383745_Monthly_rainfall_gridded_dataset_for_Africa_for_the_peri od_1970-1979_at_the_half_a_square_degree_interpolation_Inverse_Distance_Weighted). This data base seems more complete that the CRU?

**Reply 7:**

Thank you very much for this information. This data is available for 10 years and we needed a longest and homogenous dataset over the basin, hence we decided to use the CRU data since is successfully worldwide used.

**Comment 8:**

Fig. 1: Given its importance in Congo basin's water balances, I suggest to place the contour of the "Cuvette Centrale".

**Reply 8:**

We made a new Figure representing the land use instead of the elevation. In this new figure, we contoured the Cuvette Centrale.

**Comment 9:**

-Fig. 15: can be enlightened and commented thanks to the study of the evolution of annual and monthly discharges of the more important right bank tributaries like Oubangui and Sangha river (in Laraque et al., 2013). The authors can also find more "field" explanations in someone of the others reference I communicate for them mainly about the special role of the "Cuvette Centrale" partially or totally flooded depending on the hydropluviometric cycle within the Congo Basin.

**Reply 9:**

Thank you for your advice to improve this analysis. We utilized documentation from your reference list to explain some possible behavior. It is difficult to relate moisture lose over the CRB with interannual variability of the Congo and Oubangui rivers. Our goal is to identify the response of the basin in extreme periods as source or sink of moisture for itself. A deepest analysis must be done at subbasin scale to support a better hydrological reponse linked with the budget of E-P over the basin. However, we hope that the improvements in the explanation have improved this section.

*The Oubangui basin in the northeast of the CRB, should have benefited in 1982 due to positive anomalies of |(E-P)i10<0|, favouring the precipitation in the half north of the CRB. In the Oubangui basin, a decrease in runoff observed everywhere coincides with a decrease in rainfall with a time lag of 3 years, which can be explained by the sponge-like functioning of the drainage basin, where interannual variability is less important for runoff than for the rainfall series (Orange et al., 1997). An important finding of theses authors is that also the maxima and minima of annual rainfall do not completely coincide with the extreme flow events; as occurred in 1982, a severely wet year when positive anomalies of |(E-P)i10<0| over the half north of the basin including the Oubangui basin. According to the results of Orange et al. (1997), it was documented by Laraque et al. (2013) that from 1982 to 2010 the Oubangui remains in the drought phase, as the Congo returns to a phase of stability.*

**Comment 10**

-Pa. 15- Lig. 26: this sentence "For 1995, the anomalies are negative in the east and north of the basin", don't seems to correspond to the Fig 15 (year 1995). I thing necessary to change "east" by "west".

**Reply 10:**

Thank you! We have already changed the word.

**Comment 11:**

-Pa. 15 - Lig. 31: It is not exact to write "river discharge in the basin", when only the discharges used come from Kinshasa gauging station, because even if this station controls almost all the catchment, its regime is not representative of the spatial variations of the hydrological cycles of every tributaries in this basin. Please consult the references list I give to you.

**Reply 11:** Our apologize for this mistake. We made it along the entire article. It is now

Others comments:

-Why the authors don't write anything about the Hadley cells and Walker circulation?

Thank you, you are right. We hope the following sentences included in the articles are enough.

*"The air masses originating from three permanent anticyclones located to the north-west (Azores), south-west (St. Helena), and south-east (Mascarene) of the CRB converge along the Intertropical Convergence Zone (ITCZ), which separates the southerly low-level winds from the northerly winds, and the Inter-Oceanic Confluence Zone (IOCZ), separating the westerly from the easterly winds in the southern part of Africa (Samba and Nganga,*
5 *2012). In general two modes of circulation: circulation of Hadley and the Walker circulation control the movement of air masses and the climate in Central Africa, leading to moisture convergence not being uniform in the atmospheric column (Tsalefac et al., 2015, Pokam et al., 2012). Areas which are positively correlated with Congo convection are areas of the ascending arm of the Hadley cell (Matari, 2002), while the east-west oscillation of the Walker circulation modulates the moisture advection from the Atlantic Ocean and the upward motion over the*
10 *CRB (Matari, 2002; Lau and Yang, 2002)" .*

*"The rainfall-generating mechanisms are controlled by a zone of shallow depression systems in the CRB (Samba and Nganga, 2012) as well as north-south ITCZ migration (Samba and Nganga, 2012; Alsdorf et al., 2016) together with Mesoscale Convective Systems (MCS) (Jackson et al., 2009) and the African Easterly Jet along with the typical circulation of the Hadley cell (Nicholson, 2009; Pokam et al., 2012; Haensler et al., 2013)".*

15 *"In CEA Hua et al. (2016) documented for April-May-June consistently strong negative anomalies falling since the 1990s, primarily related with SST variations over Indo-Pacific associated with the enhanced and westward extended tropical Walker circulation which is consistent with the weakened ascent over Central Africa associated with the reduced low-level moisture transport".*

20 -In the document, in many cases it is necessary to change runoff by streamflow or river discharge

Reply: Thank you, the word streamflow has been replaced by the correct word in all the paper. It was a mistake to utilize this word since we don´t really use it.

-I don't think the title clearly reflect the contents of the paper, which relates more with the fluxes and exchanges
25 budget of moisture in the atmosphere of Congo basin? But this title could be preserved if the author takes more account of the hydrological characteristics and particularities of this basin, as advised in my comments.

Reply: We understand your suggestion. It is difficult to establish an accurate relationship between the water balance computed for all the CRB and the hydrology characteristics of some differentiated regions or subbasins. Nevertheless, we hope the new changes could preserve the title. We believe that a future analysis performed at
30 sub-bains scales could involves more hydrological issues.

# A Lagrangian Perspective of the Hydrological Cycle in the Congo River Basin

Rogert Sorí[1], Raquel Nieto[1,2], Sergio M. Vicente-Serrano[3], Anita Drumond[1], Luis Gimeno[1]

[1] Environmental Physics Laboratory (EphysLab), Universidade de Vigo, Ourense, 32004, Spain

[2] Department of Atmospheric Sciences, Institute of Astronomy, Geophysics and Atmospheric Sciences, University of SãoPaulo, São Paulo, 05508-090, Brazil

[3] Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE-CSIC), Zaragoza, 50059, Spain

*Correspondence to*: Rogert Sorí (rogert.sori@uvigo.es)

**Abstract.**

The Lagrangian model FLEXPART was used to identify the moisture sources of the Congo River Basin (CRB) and investigate their role in the hydrological cycle. This model allows us to track atmospheric parcels while calculating changes in the specific humidity through the budget of evaporation-minus-precipitation. The method permitted the identification at an annual scale of five continental and four oceanic regions that provide moisture to the CRB from both hemispheres over the course of the year. The most important is the CRB itself, providing more than 50% of the total atmospheric moisture income to the basin. Apart from this, both the land extension to the east of the CRB together with the ocean located in the eastern equatorial South Atlantic Ocean are also very important sources, while the Red Sea source is merely important in the budget of *(E-P)* over the CRB, despite its high evaporation rate. The moisture sink patterns over the CRB in air masses tracked forwards from all the sources follow a the latitudinal rainfall migration and are mostly highly correlated with the pattern of precipitation rate, ensuring a link between them. In wet (dry) years the contribution of moisture to precipitation from the CRB over itself increases (decreases). Particularly in dry, despite to the enhanced evaporative conditions over the basin, the vertically integrated moisture flux (VIMF) divergence inhibit the precipitation and suggest the transport of moisture from the CRB to remote regions.

## 1 Introduction

The water falling on a given area as precipitation may have been supplied to it by local evaporation and/or transpiration, alternatively it may have been advected from a remote terrestrial source, or it may have originated in evaporation from the oceans (Dirmeyer, 1999). In recent years, a great number of studies have focused on deepening our understanding of these issues, particularly the mechanisms of water vapour transport in the atmosphere and the identification of moisture sources. These issues are considered some of the major challenges in the atmospheric sciences (Gimeno et al., 2013a). Several

techniques and methods have been implemented in an attempt to address these matters; a summary of the main strengths and weaknesses of each was provided by Gimeno et al. (2012).

In respect of Africa in particular, some authors have investigated the sources of moisture for the whole continent (van der Ent., 2010; Gimeno et al., 2010, 2012), and specific regions such as the Sahel (Nieto et al., 2006; Salih et al., 2015; Keys et
5   al., 2012, 2014), Ethiopia (Viste and Sorteberg, 2013), and the wider region of West Africa (Savenije, 1995; Eltahir and Gong, 1996; Druyan and Koster, 1989). Nevertheless, the Congo River Basin (CRB), in the highly convective region of Central Equatorial Africa (CEA), is one of the least studied of the major global river basins (Alsdorf et al., 2016). Focusing on several world river catchments including the Congo, Stohl and James (2005) used the Lagrangian model FLEXPART over a period of 4 years (Dec 1999 - Nov 2003) to diagnose the net budget of *(E-P)*, where *(E)* denotes evaporation and *(P)*
10   precipitation. However, the short time-scale involved in this study was not sufficient to investigate properly the variability and other aspects of the hydrological cycle over the CRB. Gimeno et al. (2010) argued that in tropical South Africa during the austral winter the rate of evaporation is so high that it provides moisture for most of the precipitation over the Congo, and besides this according to van der Ent et al. (2010), the moisture that evaporates in East Africa is the main source of rainfall in the CRB.

15   More accurate results on the evaporative moisture sources for the CRB, together with their seasonal variations and mean contributions over a period of 25 years, are available online from the Center for Ocean-Land-Atmosphere Studies (COLA). These were calculated using a Quasi-Isentropic method, an Eulerian approach implemented in Dirmeyer et al. (2009), and the results highlight that the main evaporative sources for precipitation lie within the basin itself, in addition to the land to the east of the basin along the oriental African coasts, and the Atlantic and Indian Oceans. However, it is not yet clear what
20   the role of the CRB moisture sources is in other stages of the hydrological cycle and during extreme events in the basin. Most of the studies based on instrumental records in Africa indicate that droughts have become more frequent, intense and widespread during the last 50 years (Dai, 2013; Masih et al., 2014). The occurrence of drought is especially important in regions where economic activities are highly dependent on water resources (like the CRB), and particularly affect those African nations that are heavily reliant on agriculture (Lobell et al., 2011a, b).

25   The objectives of this study are: i) to identify the main continental and oceanic moisture sources for the CRB from a Lagrangian perspective and determine their role, including that of the basin itself in the total moisture influx to the basin, and ii) to investigate drought and wet conditions in the CRB and the relationship of these to atmospheric moisture influx.

## 1.1 Region of Study

30   The Congo River Basin (CRB) is located in central-equatorial Africa, an important part of the continent containing major rivers and dense forest (Figure 1). With an approximate area of 3,687,000 km$^2$ (Alsdorf et al., 2016), the basin includes several African countries: the Democratic Republic of the Congo (DRC), the People's Republic of the Congo, the Central African Republic, and parts of Zambia, Angola, Cameroon, and Tanzania (Chishugi, 2008). The Congo River (also known as the Zaire during at one time) is over 4,375 km long, considered to be the fifth longest river in the world, and the second

longest in Africa after the Nile River (IBP, 2015). It´s discharge shows a composite variability, which is due to the sum of its tributaries (Laraque 2001). With annual discharge of 5000 m$^3$ s$^{-1}$ at its mouth, the Oubangui River is the second most important tributary to the Congo River (mean flow 41 000 m$^3$ s$^{-1}$), after the Kasai River (8000 m$^3$ s$^{-1}$) (Briquet, 1995).

The CRB comprises the second largest continuous rainforest in the world; covering an area of approximately 1.8 Million km$^2$, the high rate of evaporation is comparable to the oceans is one of the main features of the forests, being extremely important for storing carbon and having an impact on the continental and global climate system mainly through the water cycle (Haensler et al., 2013; Marquant et al., 2015; Wasseige et al. 2015). The basin is composed basically of: a central area that contains an immense forest swamp best known as "Cuvette Centrale"; an an at the immense depression at the centre of the basin where sediment accumulation since the Quaternary alluvial deposits rest on thick sediments of continental origin, consisting principally of sands and sandstones (Kadima et al., 2011; Gana and Herbert, 2014) (Fig. 1). Here the spatial distribution of forested wetland types is controlled by topography and also by the time and the intensity of the submersion, making it the most extensive peatland complex in the tropics (Dargie et al., 2017). From a rainfall point of view, because of the topographic barrier around the "Cuvette Centrale" the Congolese central basin functions to a large extent as a closed system of precipitation, on-site evaporation and precipitation (Robert, 1946; Sorre, 1948). Located in the heart of the dense Congolese equatorial forest is the Lake Telé, an immense elliptical body of water (3 m deep for a surface of 23 km$^2$ and a maximum water storage evaluated to 55x10$^6$m$^3$) where hydrological exchanges are almost exclusively vertical with very little lateral contribution from the surrounding swamp (Lareque et al., 1998). Furthermore, the basin contains several large, permanent open water lakes including Lake Tanganyika, the largest of the African rift lakes and the world's second largest by volume and depth (Coulter, 1991; Cohen et al., 1993).

Around the central basin, there is mainly a humid evergreen dense forest and to the north and south mosaics of mixed forest; woody savannahs savannas and savannas (Marquant et al., 2015). The current distributions of different forest types correlate strongly with annual rainfall and particularly with the length and severity of dry seasons (CARPE, 2005). The CRB moist forests are the continent's main forest resource, containing an extraordinary biodiversity (Ilumbe, 2006; SCBD-CAFC, 2009) that brings important economic benefits to approximately 60 million people living in local communities (Hugues, 2011; Marquant et al., 2015). Unfortunately, in the CRB the rate of deforestation varies from one country to another. Overall, the basin had a net deforestation rate of 0.09% between 1990 and 2000, compared with 0.17% between 2000 and 2005 (Tchatchou et al., 2015). The satellite confirmed a widespread decline in greenness in the northern Congolese forest over the past decade, which is generally consistent with decreases in rainfall, terrestrial water storage, and other related aspects (Potapov et al., 2012; Zhou et al., 2014; Hua et al., 2016) like hydrological regimes (Laraque et al., 2001; Laraque et al., 2013; Wesselink, 1996).

The air masses originating from three permanent anticyclones located to the north-west (Azores), south-west (St. Helena), and south-east (Mascarene) of the CRB converge along the Intertropical Convergence Zone (ITCZ), which separates the southerly low-level winds from the northerly winds, and the Inter-Oceanic Confluence Zone (IOCZ), separating the westerly from the easterly winds in the southern part of Africa (Samba and Nganga, 2012). In general two modes of circulation: circulation of Hadley and the Walker circulation control the movement of air masses and the climate in Central Africa, leading to moisture convergence not being uniform in the atmospheric column (Tsalefac et al., 2015, Pokam et al., 2012). Areas which are positively correlated with Congo convection are areas of the ascending arm of the Hadley cell (Matari, 2002), while the east-west oscillation of the Walker circulation cell modulates the moisture advection from the Atlantic Ocean and the upward motion over the CRB (Matari, 2002; Lau and Yang, 2002). The rainfall-generating mechanisms are controlled by a zone of shallow depression systems in the CRB (Samba and Nganga, 2012) as well as north-south ITCZ migration (Samba and Nganga, 2012; Alsdorf et al., 2016) together with Mesoescale Convective Systems (MCS) (Jackson et al., 2009) and the African Easterly Jet along with the typical circulation of the Hadley cell (Nicholson, 2009; Pokam et al., 2012; Haensler et al., 2013).

## 2 Data and Methodology

The analysis covers the period 1980-2010. The drainage area of the Congo River Basin (CRB) (Figure 1) was defined using geo-referenced watershed boundaries on a 30 arc-second resolution map (a Hydrobasin product of HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales), Lehner and Grill (2013)). This was used to obtain the spatial mask of the basin, which was later implemented in the computations.

The methodology implemented here is based on the Lagrangian model FLEXPART developed by Stohl and James (2004, 2005). The model allows us to track the parcels backwards and forwards; thus Tthe model outputs were used to compute the gain and loss of humidity along track trajectories of air particles leaving and arriving in the CRB. The model allows us to track the parcels backwards and forwards. The backward analysis was utilized for the, allowing the identification of the moisture sources for the CRB and the forward to obtain then their climatological moisture supply and the relationship to the precipitation in it. The approach implemented here has been widely and successfully applied to study the atmospheric branch of the hydrological cycle (e.g., Stohl and James, 2004, 2005; Nieto et al., 2008; Gimeno et al., 2010; Gimeno et al., 2012; Chen et al., 2012; Viste and Sorteberg, 2013; Drumond et al., 2014).

In this method, the atmosphere is divided into N evenly distributed "particles" or "parcels", whose advection is described by Eq. (1):

$$dx/dt = v \ [x(t)], \tag{1}$$

where x is the position of the parcel and $v \ [x(t)]$ is the wind speed interpolated in space and time. The gain (through evaporation from the environment $e$) or loss (through precipitation $p$) of specific humidity ($q$) by each parcel is calculated following Eq. (2). Along individual trajectories $q$ fluctuations can occur for nonphysical reasons (e.g., because of $q$

interpolation or trajectory errors), a limitation partly compensated by the presence of so many particles in an atmospheric column over the target area, thus:

$$(e - p) = m(dq/dt), \qquad\qquad (2)$$

where additionally m is the mass of a particle. By integrating over an area of interest it is possible to obtain the net effect of the moisture changes in all the particles in the atmospheric column and, as a consequence, a diagnosis of the surface freshwater flux, hereafter represented by *(E-P)* (Stohl and James, 2004). It is worth mentioning that in some regions atmospheric moisture is not precipitated but just flows through; while in others the convergence of moisture ensures that precipitation occurs (Pokam et al., 2012). A region is then considered a moisture source when *(E-P)>0*, and the net moisture budget of the particles tracked is favourable to evaporation from the environment to the particles. In moisture sink regions the opposite occurs, i.e., the associated moisture budget is favourable to moisture loss from the tracked particles to the environment. A analysis backwards in time tells us where the atmospheric moisture in the air masses over the CRB came from, enabling us to identify the main oceanic and continental sources of moisture. The analysis was applied for 10 days, which is the average residence time of water vapour in the atmosphere (hereafter we use *(E-P)i10)* (Eltahir and Bras, 1996; Numaguti, 1999).

The Lagrangian data used in this work were obtained from a FLEXPART v9.0 experiment executed on a global domain, in which the atmosphere was divided into about 2.0 million uniformly distributed particles. FLEXPART uses ERA-Interim reanalysis data (Dee et al., 2011) available at 6 h intervals (00, 06, 12, and 18 UTC) at a resolution of 1° at 61 vertical levels, from 0.1 to 1000 hPa, with approximately 14 model levels below 1500 m and 23 below 5000 m. This is important because the transport of water vapour occurs mainly in the lower troposphere, which is clearly affected by the earth's topography (Peixoto and Oort, 1992).

To ensure the selection of the most important annual moisture source regions for the CRB, a threshold was used to delimit these, defined by the value of the 90th percentile calculated from the annual *(E-P)>0* values integrated over the 10 days of transport. This value acts as boundary to delimit those regions where air masses gain more humidity on their journey to the CRB, representing the 10% of grid points with the highest positive values of *(E-P)i10* on the map. This criterion was applied for similar purposes by Drumond et al. (2014, 2016a, 2016b). The CRB itself is ~~also~~ considered a source of moisture, permitting ~~,~~ to evaluate its role in the local budget of *(E-P)*. ~~and it its role in recycling is therefore evaluated here.~~ Tracking the air parcels forwards from each of the delimited moisture sources allows us to compare their contributions and thus the importance of each in the total moisture influx to the CRB.

Data for precipitation were obtained from the CRU TS v.3.23 database (Harris et al., 2014) with a spatial resolution of 0.5°. The runoff, the geopotential at 850 hPa, and the vertical integrated moisture flux (northwards and eastwards) form part of the Era Interim Reanalysis Project (Dee et al., 2011), with a resolution of 1°x1° in latitude and longitude. The corrected monthly

mean discharge of the Congo River recorded at the gauging station at Kinshasa (4.0º S, 15.3º E) was provided by the Global Runoff Data Centre (GRDC). To estimate the ~~total~~ actual evaporation over the moisture sources we use two state-of-the-art base data sets: OAFLUX and GLEAM. The monthly ocean evaporation data are obtained from the OAFLUX project, which uses surface meteorological fields derived from satellite remote sensing and reanalysis outputs produced from the NCEP and

5      ECMWF models (Yu et al., 2008). The monthly evaporation from the land is estimated from GLEAM (Global Land Evaporation Amsterdam Model) v2a data, which takes into account a set of algorithms including transpiration, bare-soil evaporation, interception loss, open-water evaporation and sublimation (Miralles et al., 2014), all of which are important considering the dense forests of the CRB.

The selection of global datasets was decided because documented gaps in hydrological information of the CRB (Tshimanga,

10     2013). However, observational data series are available on the SIEREM website (Boyer et al., 2006) mainly to the north part of the basin. In this work, the analysis covers the period 1980-2010 taking into account the availability of ERA-Interim from 1980 and the river discharge data available at Kinshasa gauge station until 2010.

The role of general circulation in the hydrological cycle can be shown clearly through maps of vertically integrated

15     atmospheric moisture flow (Peixoto and Oort, 1992). Also known as Vertically Integrated Moisture Flux (VIMF), this allows readers to compare moisture transport under an Eulerian perspective (Drumond et al., 2014); consequently these maps should lend support to explanations of moisture budget calculated using FLEXPART.

The methodology used to quantify drought or wet conditions in the CRB is based on the Standardized Precipitation

20     Evapotranspiration Index (SPEI), which is a multi-scalar drought index that considers the effect of both precipitation and atmospheric evaporative demand (AED) (Vicente-Serrano et al., 2010). The SPEI for the CRB was calculated at time scales from 1 to 24 months using precipitation and reference evapotranspiration (ETo) obtained from the CRU TS v.3.23 dataset. The criterion of McKee et al. (1993) was used to identify those years of severe and extreme drought and wet conditions (according to the SPEI threshold of +/-1.5). Hydrological drought conditions were quantified at the gauging station of

25     Kinshasa using the Standardized Streamflow Index (SSI) (Vicente-Serrano et al., 2012).

## 3 Results and Discussion

### 3.1 Climatology: Rainfall and runoff over the basin and Congo River discharge

The annual cycle of precipitation over the CRB is depicted in Figure 2. The most notable feature of the monthly patterns is the latitudinal migration of the maximum precipitation ~~maximum~~ throughout the year, which leads to different seasonal

30     patterns over the territory ~~according to~~ (Bultot, 1971; Chishugi ~~(~~2008). Based in previous results Mahe (1993) defined four great climatic zones over the Congo Basin: the North (Ubangi River Basin), where the influence of the North African continental air mass is prominent; the South (Kasai River Basin), which is influenced by South African air masses; the eastern and south-eastern parts of the basin (Lualaba River Upper Basin), which are influenced by the humid Indian Ocean

air masses; and the Center-West, where the climate is controlled by the Atlantic Ocean. Nevertheless In fact, the evaluation of the impact of rainfall on various sectors and its distribution throughout the annual cycle may be as important as the total annual rainfall (Owiti and Zhu, 2012). During January, February and March, the southern half receives more precipitation, while April is a transitional month with maximum rainfall in the west-central and northeast parts of the basin. From May to August the rainfall pattern appears homogeneous and reveals that the majority of the average precipitation occurs in the northern part, coinciding with the northward excursion of the ITCZ between February and August (Nicholson and Grist, 2003; Suzuki, 2011). From May to October the northeast of the CRB receive the highest rainfall, favouring the Oubangui catchment, a right bank tributary of the Congo River that drains at the Bangui gauge station an area of 488500 km$^2$ (Runge and Nguimalet, 2005). In September the rainfall increases to the south affecting the centre of the basin, with the greatest extension in October. In November, the central and southwestern parts of the CRB receive more rainfall and during December there is also an extension to the southeast. The regime of precipitation over the CRB is clearly differentiated by a latitudinal oscillation of maximum accumulated values, in accordance with several studies reviewed by Alsdorf et al. (2016) and within an interannual variability higher in the north and south than in the central units of the basin (Mahe, 1993).

Monthly average precipitation for the whole basin shows an annual cycle with two maximum peaks during March-April and October-December, with values greater than 4.5 mm day$^{-1}$, each accounting for 21% and 32.6% of the mean annual rainfall in the CRB, respectively (Fig. 3). During June and July the average rainfall reaches its lowest level of around 2 mm day$^{-1}$. This cycle is similar to that described by Washington et al. (2013), who compared the Congo rainfall climatology through several datasets obtained from reanalysis and ensemble models. However, they argued that the maximum rainfall in the basin occurs from March to May and from September to November, while the minimum occurs in June-August. The differences in monthly average precipitation may be due to the areas used; they used a box region over equatorial west Africa while we use the CRB boundaries. In the period 1951-1989 towards Central Africa, the rainfall trend is at first much less clear near the Atlantic Ocean, and then becomes more intense towards the interior of the continent (Olivry et al., 1993). It is also noticed in the results of Hua et al. (2016) for Central Equatorial Africa (CEA), who obtained a trend of 0.21 mm d$^{-1}$ per decade ($p<0.01$) for the period 1979 – 2014 utilizing precipitation data from GPCP.

The mean annual cycle of runoff in the CRB (Fig. 3) follows the same annual cycle as rainfall although it is always lower, varying between maximum values of 3.0 and 3.5 mm day$^{-1}$ during November-March and minimum values below 1.5 mm day$^{-1}$ during July and August. The long-term distribution of precipitation and runoff over the African continent is almost the same (Siam et al., 2013), but the highest values of runoff are concentrated in the heart of the equatorial forest along the Middle Congo River branch (Alemaw, 2012), with these wetlands receiving the majority of their waters from upland runoff (Lee et al., 2011) and several large rivers draining into the Congo in this middle section; the largest of these is the Ubangi, at the north of the Congo Basin (Harrison et al., 2014). The interannual correlation calculated between the two series (precipitation and runoff) over the CRB is high, $r = 0.73$ (significant at $p<0.05$) and $r = 0.72$ with a one-month lag. Fig. 3

shows that from March onwards the runoff reflects a one-month lag compared with precipitation. In general, in a steady state, the precipitation exceeds the evaporation (or evapotranspiration) over the land and the residual water runs off, resulting therefore in a continental freshwater discharge into the oceans (Dai and Trenberth, 2002). This also occurs in the CRB, where monthly values of precipitation minus the actual evapotranspiration obtained from the GLEAM dataset seem to follow the same annual cycle as precipitation (Fig. 3). In June *(P-E)* has a negative value, which means that on average there is more evaporation in the basin than precipitation [as in Dai and Trenberth (2002) and Siam et al. (2013)].

The mean annual discharge of the Congo River is 38617.4 m$^3$ s$^{-1}$, as calculated from the GRDC monthly discharge streamflow values registered at the Kinshasa-Brazzaville gauging station in the period 1980-2010. In the secular chronic of the hydro-pluviometric data (1903-2010) recorded at Brazzaville gauge station, close to Kinshasa and analysed by Lareque et al. (2013), the average flow of the Congo River from 1982 to 1994 is under the annual mean, followed by a period of stability from 1995 to 2010. At long-term results of Mahe et al. (2013) pose the Congo River runoff time series follows trend; also that the minimum runoff (here these author refers runoff as discharge) shows a lesser inter-annual variability than that of the average or of the maximum. Future climate projections (21st century) despite to be uncertain, show a basin average increase in both rainfall and evaporation, but the total increase in rainfall tends to be higher than the increase in evaporation and result in most scenarios the runoff is increasing (Beyene et al., 2013). For the northern sub-basins of the Oubangui and Sangha Rivers Tshimanga and Hughes (2012) obtained that more than 10% decrease in total runoff as a consequence of relatively little increase in rainfall and a consistent increase in potential evapotranspiration.

The annual cycle of discharge (which is very similar to the precipitation and runoff) shows climatological maxima during November-December (Fig. 3) with values above 48000 m$^3$/s, while in July and August the minimum is less than 30000 m$^3$/s. Despite this, a difference is seen during March when high precipitation and runoff occur, but the discharge is low. During the next few months the precipitation and runoff decrease while in contrast the discharge increases, reaching a maximum in May. This lag should reflects the time needed for the surface runoff to reach the river mouth and but also could be the groundwater contribution (Dai and Trenberth, 2002, 2008; Marengo, 2005; Rwetabula et al., 2007; Sear et al., 1999), as documented by Materia et al. (2012) using data recorded at Brazzaville station, about 400 km upstream of the river mouth. The direct relationship between precipitation over the basin and the discharge has a correlation of 0.52, which increases to 0.66 for a one-month lag (both statistically significant at *p*<0.05), confirming the lagged response mentioned earlier. Briquet, (1993) pointed out that a translation of the stability of this hydrological regime is shown by a high (low) frequency of floods occurrence on close dates from one year to the other.

### 3.2 Identification of the moisture sources

In December, January and February over the CRB, areas of *(E-P)i10>0* (moisture sources) are represented by reddish colours, and are located over the northern half of the CRB and over the river mouth (Fig. 4). Negative values *(E-P)i10<0*

(sinks), in blueish colours, cover the southern part of the CRB. Outside the boundaries of the ~~CRB~~ basin, *(E-P)i10>0* values can be seen spread over the northeast of the continent, the Mediterranean Sea, the Red Sea, the Arabian Sea, and the tropical-east South Atlantic Ocean. Negative values are observed in the southeast of the basin, the tropical-west Indian Ocean, and the equatorial Atlantic Ocean around the Equator. For these three months the moisture convergence over central-equatorial

5    Africa between 0°-20°S, together with a divergence belt to the north of 0°, can be seen. The patterns of atmospheric divergence and convergence are associated with high-pressure systems as well low pressures at the Equator and in the ITCZ zone, approximately. The deep convection of the ITCZ depends on the contribution of water vapour by the surface moisture flux, supplied as surface latent heat flux, and the horizontal moisture flux in the lower free atmosphere (Suzuki, 2011). The Vertically Integrated Moisture Flux (VIMF) identifies moisture reaching the CRB from divergence zones in the Sahel and

10   the Arabian Sea. It is extremely important to assess the VIMF because in Equatorial Central Africa the seasonal variability of the spatial gradient of precipitation recycling is regulated by both the direction and the strength of the moisture flux (Pokam et al., 2012).

In March the pattern of *(E-P)* changes over the basin, with the establishment of intense moisture sinks located to the centre-

15   west. March seems to be a transitional month, and in April the pattern of *(E-P)* undergoes a more obvious change characterized by moisture loss over the northern half of the basin, a region that acts as a source in the months before this. Despite this, in both months the VIMF remains flowing from ~~west to east~~ east to west over the basin, meanwhile the fields of convergence and divergence of moisture flux are not that different from previous months, instead highlighting a decrease in the divergence over the Arabian Sea (Fig. 4).

20   Just as in April, from May to September the budget of *(E-P)* over the basin is characterized by negative values in the northern half, in agreement with the maximum precipitation rates for these months (see Fig. 2). Specifically for June to August (the driest months) these values are confined to the northern part of the basin, while an evaporative condition prevails over the rest of the CRB. This demonstrates the ability of FLEXPART to simulate moisture losses in the basin associated with convective precipitation, as well as rainfall migration.

25   Beyond the CRB, from May to September the source areas *(E-P)i10>0* over the Arabian Sea diminish and the VIMF changes from its previously southwestward direction, which means that moisture transport from this region to Africa is no longer favoured. The *(E-P)i10* patterns are very similar to those of previous months for the other regions. During these months, in the equatorial Indian Ocean the moisture sinks are less intense than in previous months. At the same time a latitudinal displacement of moisture convergence and divergence zones occurs over central-equatorial Africa; a joint analysis

30   of the maximum precipitation and convergence of the VIMF provides a rough estimate of the position of the ITCZ (Žagar et al., 2011).

Locations where *(E-P)i10>0* are generally accompanied by moisture flux divergence. However, the Arabian Sea supplies moisture to the CRB from May to October (blueish colour in the left-hand panels); specifically during June-September the

VIMF shows an anticyclonic circulation over the Indian Ocean, which induces an intense north-east flow from the Arabian Sea to the Indian Peninsula, in fact this is an important moisture source for Indian monsoon rainfall (Levine and Turner, 2012).

5    The sink regions cover almost the whole of the CRB in October and November, when the southeast Atlantic Ocean, the continental regions in the east and north of the basin, and the southwest Indian Ocean all act as moisture sources. A transition of the scheme of moisture source regions takes place in November when once again over the Arabian Sea the *(E-P)i10>0* values appear (Fig. 4). This coincides with the beginning of the summer in the southern hemisphere and the decay phase of the Indian monsoon. The VIMF illustrates the moisture transport from the source regions to an area to the south of

10   0º in central-equatorial Africa, which enhances the precipitation process over the CRB in accordance with the southward movement of the ITCZ over Africa.

The climatological annual backward average of 10-day integrated *(E-P)* obtained from the Congo River Basin is presented in Fig. 5. This figure ~~which thus~~ summarizes the most important moisture sources for the CRB throughout the year. As discussed earlier the boundaries of the moisture sources regions were identified by imposing the 90th percentile (p90)

15   threshold of the annual *(E-P)i10>0* values. This equates to 0.43 mm day$^{-1}$, denoted in Figure 5 by the dashed lines. Five continental (C) and four oceanic (O) moisture sources were defined (Fig. 6). The five continental regions are located as follows: central and northeastern Africa (C1), centre-west part of the continent on both sides of Equator and at the river mouth (C2), from the river mouth along the Atlantic coast (C3), the east of the CRB extending along the west coast of Africa from the north of Somalia and Ethiopia to approximately 20ºS (C4), and finally the CRB itself. The four oceanic sources are:

20   the Red Sea (O1), the Arabian Sea (O2), the eastern part of the tropical-equatorial South Atlantic Ocean along the coast of Africa (O3), and finally the tropical west Indian Ocean (O4). Moisture source regions are not stationary, varying in intensity from year to year, and expected to change in the future (Gimeno et al., 2013b). In addition, their role may change given the high decadal- and century-scale variability of the African climate (Masih et al., 2014). Nevertheless, these source regions provide insight into the mechanisms by which atmospheric moisture transport takes place towards central equatorial Africa,

25   and how these impact precipitation in the CRB. A combination of factors may influence the role of each in the moisture influx into the CRB, such as the amount of water evaporated, the distance between each source and its target area, the atmospheric circulation, and the residence time of water vapour in atmosphere.

A comparison with the evaporative moisture sources for the CRB obtained using the quasi-isentropic method and available online (http://cola.gmu.edu/wcr/river/basins.html) confirms the importance of recycling in the CRB, in agreement with our

30   results (Fig. 4, 5). There are nevertheless some differences at the annual scale, in that parts of the northern half of the basin act as moisture sinks (Fig. 5), and that the quasi-isentropic climatology mentioned above considers the entire basin to be an evaporative source. Another clear difference is the Indian Ocean, where our results reflect more clearly the seasonal latitudinal migration of the evaporative regions over the year.

### 3.3 Freshwater evaporation in the sources

An analysis of the evaporation rate over the moisture sources may support our understanding of their role in the moisture uptake ~~in~~ for the CRB over the year. It is most important to note that although the ~~total~~ mean evaporation over a region considered to be a moisture source, quantified here using GLEAM and OAFLUX, can be high, its contribution for precipitation over the CRB might not be, because it could be providing moisture for precipitation in other target regions as well. The geographical location of the basin allows it to receive moisture from the Atlantic and Indian Oceans, as well from land regions around the basin, as Fig. 6 shows. Oceanic evaporation is highly important if we consider that evaporation from the ocean surface equates to roughly 84% of the total amount of water evaporated from the planet (Oki, 2005), and the role of the oceans is decisive in continental precipitation (Gimeno et al., 2010). The mean annual evaporation from the sources is given in Table 1 using data from OAFlux and GLEAM for the ocean and continental regions, respectively. On average, O4 and O1 are the most evaporative sources while O3 is the least evaporative. Among the continental sources the most evaporative are C2, CRB and C3.

Because the sources are located in two different hemispheres, they should have different annual evaporation cycles (Figure 7). From the FLEXPART backward experiment from the CRB, monthly positive values of $(E-P)i10$ were calculated over each source (hereafter E-FLEX) to compare over the year the average of evaporation ~~from~~ over the sources with the moisture average uptake from each source to the CRB. $(E-P)>0$ can be discounted after $(E-P)$ has been integrated without altering the general patterns of net precipitation, where $(E-P)>0$ is discounted using a monthly or longer time scale (Castillo et al., 2014). In Figure 7 it is possible to observe both series for comparison, E-GLEAM (evaporation data over continental sources) or E-OAF (for oceanic ones) and E-FLEX. On the African continent, in C1 from May to October (boreal summer) E-GLEAM is higher than E-FLEX, and the opposite takes place in the other months, indicating when this source becomes more efficient in providing moisture to the CRB (grey shaded areas in Fig. 7, C1). The next continental source is C2 which shows the higher land annual evaporative value (Table 1). In this source the annual cycle of E-GLEAM and E-FLEX differs from C1. Over this region the E-FLEX values are greater than the local evaporation calculated using the GLEAM dataset during February and from June to October (grey shaded areas in Fig. 7, C2). Despite the local evaporation E-GLEAM does not show any great variations over the year, varying from 2 to 3 mm day$^{-1}$, the E-FLEX shows a bimodal cycle with a minimum in May (~2 mm day$^{-1}$) when major local evaporation occurs, and a maximum in August (~4.2 mm day$^{-1}$) when local evaporation is at its lowest. This behaviour illustrates that it is possible to have moisture available in the atmosphere (higher E-GLEAM values) but less humidity is taken up by air masses and then carried towards our target region (lower values of E-FLEX); in this mechanism the rainfall over the region must plays a key role since the E-FLEX could be lowest than E-GLEAM as a result of high P values over the region. The grey shaded areas in Fig. 7 indicate those months when the transport of moisture is favoured from the source to the CRB. Over the course of several days an air parcel may undergo multiple cycles of evaporation and precipitation (Sodeman, 2008) and in our case after integrating monthly data over 10 days it is hardly surprising that the E-FLEX values could be greater than local evaporation. Nevertheless, C2 is a land region,

where the recycling concept is most useful because moisture for evaporation is limited by precipitation, whereas over the oceans the surface is clearly wet regardless of whether it rains or not (Trenberth, 1999). The C3 source, separated from C2 by the Congo River mouth, follows a similar annual evaporation cycle to C2, but with lower values (<1 mm day$^{-1}$) during June-October (Fig. 7, C3). In addition, the E-FLEX values are higher than E-GLEAM in February and July-September. In the months of March-May and November C3 becomes less efficient at providing moisture to the CRB. For the continental source C4, the annual cycle of local evaporation (E-GLEAM) is similar to C2, C3 but the moisture uptake by air masses tracked backwards from the CRB (E-FLEX) over C4 is always greater than E-GLEAM (unless in February), indicating that this source is very efficient in terms of moisture uptake for the CRB, agreeing with results of van der Ent et al. (2014). For CRB the annual cycle of the E-GLEAM is characterized by maximum values during December-May and a minimum in July-August (Fig. 7, CRB). In January-February, April-October, and December, E-FLEX is higher than E-GLEAM, in accordance with the decreasing precipitation over the basin (Fig. 3). This is understandable because the moisture uptake (E-FLEX) over the basin itself must be favoured when the precipitation over it decreases. Comparing the precipitation annual cycle in the CRB (Fig. 3) with E-GLEAM (Fig. 7), it can be seen that both show the same annual cycle, but they show opposite behaviour from E-FLEX (Fig. 7, CRB). This relationship describes a scheme in which the precipitation and evaporation are strongly lineally related; in fact the evaporation as a source for precipitation over land depends on the availability of surface moisture, which in turn depends upon the disposition of precipitation once it hits the ground (Trenberth, 1999). But, the moisture uptake is the opposite, determining when the source is more effective in providing moisture for itself. Moreover, This relationship is not strictly interdependent because it could be modulated by moisture income from the other sources or transported outside the boundaries of the target region (the basin).

Regarding the continental oceanic sources of moisture, in the CRB the continental evaporation recycling efficiencies are high, and strong local recycling develops, or evaporative fluxes at least, and it is these that contribute to precipitation elsewhere on the continent throughout the year (van der Ent et al., 2014). The second In the source O1 with the major monthly the mean annual E-OAF is O1 (4.60 mm day$^{-1}$). This source is, located on the Red Sea, where the oceanic evaporation rate is the highest in the world according to (Abdulaziz, (2012). After reviewing many studies Sofianos et al. (2002) confirmed several differences in the mean annual evaporation rate for the Red Sea, but it was estimated at around 2.06 m year$^{-1}$ (~5.6 mm day$^{-1}$). Figure 7 shows the annual cycle of evaporation (E-OAF) in this source, which is characterised by higher values during the boreal winter months and minimum values in summer, in accordance with Bower and Farrar (2015). Monthly E-FLEX values obtained over this source follow the same annual cycle as E-OAF but with lower values. As for O4, This means that despite to be a high evaporative source, the moisture contribution from O1 to the air masses in transit to the CRB is less than that which it must provide itself to the atmosphere; converting it into a region that is not efficient in terms of the moisture supply to the CRB. In contrast it seems an important moisture source during December-February over continental areas to its Northeast and during June-August to the remote area of the Indian Peninsula (Gimeno et al., 2010). Located in the Arabian Sea, the O2 source shows two evaporation peaks during December-January and June,

and two minima in April and September (Fig. 7). This cycle was also noted by Sadhuram and Kumar (1987), who showed that the maxima are related to strong winds, and the minima are a result of low wind speeds together with weak vapour pressure across the Arabian Sea. The moisture uptake over this source between April-October is almost insignificant, but the evaporation from OAFlux is greater, which means that this source is not efficient in delivering moisture to the CRB, because during these months it instead contributes to the Indian monsoon (Levine and Turner, 2012). In the Atlantic (O3) has the smallest monthly average evaporation rate among all the oceanic sources throughout the year ($<1$ mm day$^{-1}$), showing a negligible annual cycle. Materia et al. (2012) determined that the evaporation rate from the ocean surface is lower due to the fact that part of this oceanic region is affected by the huge freshwater discharge of the Congo River, contributing to a decrease in Sea Surface Salinity (SSS) and Sea Surface Temperature (SST). Despite this, E-FLEX is greater than E-OAF except for during April and May, when the moisture uptake over this source is less than 1 mm day$^{-1}$. The moisture uptake has two peaks, one in February and the other in September-October. The last oceanic source is O4, the most evaporative and characterized by a maximum average E-OAF in May-July ($>5.5$ mm day$^{-1}$) and a minimum at the beginning and end of the year (Fig. 7, O4). This behaviour is in accordance with the results of Yu et al. (2007), who argued that the enhancement of evaporation occurs primarily during the hemispheric winter (defined as the mean of December–February for the northern hemisphere and June-August for the southern). The positive values of E-FLEX over this source (O4) are lower and quite different from the mean E-OAF during all months. This means that on average this source is not very efficient in supplying moisture to the CRB. The efficiency of a region providing moisture to precipitation for a target area depends on the amount of evaporated water that reaches it, and not just on the initial evaporation rate. In this mechanism we must highlight the importance of the atmospheric circulation patterns in determining the water vapour transport, and also, that moisture uptake from each source can be completely different from the evaporation in it.

**3.4 Moisture contribution from the sources. Forward analysis.**

Having identified the moisture sources regions, and their efficient providing moisture to air masses in transient to the CRB, we determined the quantities and locations of the moisture loss over the CRB from those particles leaving each source using forward tracking. For this purpose, a forward experiment with FLEXPART was used, integrating particles forwards over 10 days. FLEXPART was used to compute the changes in *(E-P)* by tracking air parcels regardless of whether it rains or not, but in this case we computed the result just for those particles arriving in the CRB that lost humidity, hereafter moisture contribution.

Fig. 9 shows the monthly variation in the percentage of moisture contribution to the CRB with respect to the total income and the monthly mean precipitation over the CRB from CRU TS v.3.23 data (Harris et al., 2014). The basin itself turns out to be the most important moisture source throughout the year, contributing more than 55% each month (green line) to the total moisture supply from all the sources to the basin. The contribution from each of the remaining sources does not exceed 20% of the total. This result suggests the importance of moisture recycling over the basin, which differs from the result of van der

Ent et al. (2010) who argued that the main source of rainfall in the Congo is moisture evaporating over East Africa, particularly over the Great Lake regions. This is probably a consequence of the method used; their approach takes account of how much of the evaporated water returns as precipitation to the same region (regional evaporation recycling), and what part of it is advected out of the region.

5 The annual cycle of the percentage moisture supply with respect to the total moisture contribution to the basin is quite similar for the C1 and C3 sources, at less than 4%. C2 and C4 are the most important continental sources (after the CRB itself) supplying moisture for the CRB across the year; they are located to the east and west, respectively, of the basin, and play opposite roles throughout the year. The moisture supply calculated from FLEXPART, $|(E-P)i10<0|$, for C4 follows the precipitation annual cycle in the basin particularly well. From the oceanic sources, the moisture contributions to the basin

10 from O1 and O2 with respect to the total are less important than those from O3 and O4. It can be seen that the contribution from O3 increases and is thus important when the contribution decreases from the CRB itself, confirming the importance of moisture transport from the Atlantic Ocean. From the Indian Ocean, the contribution of moisture of O4 is at a maximum in January-February and July-August (>15%) when the precipitation rate decreases over the CRB (Fig. 3). The maximum monthly contribution from O4 occurs in April-May (~8%).

We analysed separately the percentage of moisture supplied from land-based and oceanic sources to the total moisture inflow to the CRB for the period 1980-2010. The results confirm that over the whole year near or more than the 80% of the total moisture contribution to the basin origins in land sources, highlighting that ~~the highest percentage (>50%)~~ more than the 50% of the total ~~of the moisture contribution~~ comes from the CRB itself (Fig. 10~~, green bars~~). Evaporation as a source for

20 precipitation over land depends on the availability of surface moisture, which in turn depends upon the disposition of precipitation once it hits the ground (Trenberth 1998). In fact, according with Eltahir (1998) the soil moisture conditions over any large region should be associated with relatively large boundary layer moist static energy, which favours the occurrence of more rainfall. This hypothesis was also confirmed for West African monsoons by Zheng and Eltahir (1998). In this line van der Ent and Savenije (2011) quantified the spatial and temporal scale of moisture recycling, independent of the

25 size and shape of the region; through this method they found that about the 70% of the precipitation in the center of the South American continent is of terrestrial origin like in many parts of Africa, but specifically in the CRB where occur a strong moisture feedback. For Central Equatorial Africa (CEA) Pokam et al. (2012) and Trenberth (1999) reported a recycling ratio (the fraction of rainfall coming from evapotranspiration and not from moisture advected to the target region) higher than obtained for the Amazon in studies of Eltahir and Bras (1994) and Burde et al., (2006). In the CRB as already

30 was commented, the role of forests is also fundamental as they sustain atmospheric moisture through evapotranspiration, which is of utmost importance for the region's water resources, specifically the evergreen forest region (Matsuyama et al., 1994; van der Ent and Savenije, 2011). The key role of continental moisture sources has been also documented for monsoonal wettest regions like the Western Mexico (Bosilovich et al., 2003; Domínguez et al., 2008), Sudamérica (Drumond et al., 2014; Keys et al., 2014) and the Indian region (Misra et al., 2012; Pathak et al., 2015).

The annual role of the moisture sources contributing to precipitation in the CRB is shown in Table 2 as the percentage of the total annual $|(E-P)i10<0|$ amounts over the CRB. The CRB itself is responsible for 59.3% and is the most effective source, followed by C4 with 12%, and O3 with 11.5%. These three sources together account for 82.8% of the total moisture supply to the CRB in the climatological year. The remaining sources contribute 17.2% of the total precipitable moisture. The O1 source, located in the Red Sea, is responsible for just 0.2%.

In order to analyse the joint linear temporal variability, t~~T~~able 3 shows the significant ~~results of a linear~~ correlation values ~~analysis indicating the relationship~~ obtained between monthly series of evaporation, precipitation, runoff~~,~~ in the CRB ~~and~~ river discharge at Kinshasa gauge station ~~series~~ and ~~using the~~ $|(E-P)i10<0|$ from each source over the CRB and the total $(E-P)i10<0$ from all the sources (T). All the correlation coefficients are positive and statistically significant at 95%, with the exception of that obtained between $|(E-P)i10<0|$ over the CRB from C2 with the evaporation in the basin and the Congo River discharge at Kinshasa gauge station. As expected correlation are greater with precipitation than evaporation as $|(E-P)i10<0|$ may be associated with rainfall process over the CRB. In ~~several~~ most of the cases the initial correlation values with evaporation and those followed obtained with the rest of variables decrease as ~~between the precipitation and the river discharge is reduced as~~ as the consequence of the lagged response of the hydrological system; a behaviour best appreciated for the correlation with $|(E-P)i10<0|$ over the CRB, obtained in the air masses tracked forward in time from the CRB itself and for the Total contribution. In the evolution of the correlation values showed in Table 3, $|(E-P)i10<0|$ are best correlated with the Congo River discharge at Kinshasa gauge station than with evaporation in the basin unless for $|(E-P)i10<0|$ obtained in air masses from O4. ~~In other cases, such as the correlation of $|(E-P)i10<0|$ from O1 and C3 with runoff, the coefficient obtained is greater than that obtained with precipitation.~~

Fig. 10 shows the spatial relationship between the moisture supply from the sources and the precipitation over the CRB. The seasonal $|(E-P)i10<0|$ mean values over the CRB are plotted: December-February (DJF), March-May (MAM), June-August (JJA) and September-November (SON). Each map shows the correlation (shown bottom right) of these patterns with the respective climatological precipitation pattern over the basin (not shown).

The moisture sinks for the air masses transported from C1 to the CRB during DJF are more intense (~ -1.5 mm day$^{-1}$) on a belt located in the central-north part of the basin extending beyond it and to the south (Fig. 10~~1~~). In MAM the maximum moisture loss moves northwards, and it almost disappears altogether in JJA, while for SON the moisture loss covers the entire CRB with major sinks located in the northern half, in agreement with the high rainfall observed during these months (see Fig. 2). For SON the best correlations were those between the patterns of $|(E-P)i10<0|$ from C1 and precipitation over the CRB ($r=0.50$). From C2, those sources located to the west of the CRB, the greatest moisture contribution occurs over the west of the basin. In MAM and JJA the $|(E-P)i10<0|$ patterns are observed over the northern half, and the best correlation was obtained for JJA ($r=0.63$). Contrary to what happens with moisture loss over the basin from C2, the greatest moisture

sinks over the CRB for air masses tracked forwards from C3 are mostly positioned to the southwest (best observed for SON and DJF). In MAM and JJA, the sinks are mainly located in the northern half of the basin. From C4 (located to the east of the CRB) the sinks over the CRB decrease in intensity from east to west (the eastern areas show the most intense sinks, >6 mm day$^{-1}$). It is worth remembering that in southern equatorial Africa, and specifically in the CRB region, the precipitation pattern provides a mechanism of atmospheric communication between east and west Africa, these two equatorial regions being generally treated as climatically separate units (Dezfuli et al., 2015). As expected, during SON and DJF (rainiest months) the pattern of $|(E-P)i10<0|$ is more intense. The correlations vary between 0.36 and 0.43, all significant for $p<0.05$. Throughout the year the CRB is the most important moisture source for itself (Fig. 9~~9 and 10~~), which is confirmed by the intensity of the values in the $|(E-P)i10<0|$ pattern (Fig. 10~~1~~). In DJF and SON greatest moisture sinks (>12 mm day$^{-1}$) cover the major part of the centre and south of the basin. In MAM and JJA they are similar to the other sources. The correlation of these patterns with the spatial precipitation was the highest obtained ($r>0.63$).

We previously discussed how the oceanic source O1, despite being an important evaporative region, is not an effective moisture source for precipitation over the CRB. This fact can also be seen in the pattern of $|(E-P)i10<0|$ over the CRB in Fig. 10~~1~~, where the values are low and oscillate around -0.5 to 0 mm day$^{-1}$. The pattern also reflects the north-south variability of the precipitation over the year. From the O2 source, located in the Arabian Sea, the greatest moisture contribution occurs in the east and northeast part of the basin, apart from in JJA when the pattern is confined to the northwest and the moisture loss is lower. The O3 source, in the east-tropical Atlantic Ocean, is the most important oceanic source for the CRB, as shown in Table 3. In DJF the major moisture sinks are over the southwest of the basin, in MAM and JJA the moisture loss is mainly over the central and north of the basin, and during SON it is over the east. These patterns show a good correlation with rainfall spatial distribution ($r>0.43$). From O4, located in the West Indian Ocean, the greatest moisture contribution during DJF occurs over the south, and along a longitudinal belt in the central of the basin in MAM; in JJA the major contribution can be detected over the northern part of the basin. During SON when the moisture loss from O4 covers practically the whole territory, with the highest loss over the east, the correlation with the precipitation pattern is negative, however ($r=-0.18$). The highest precipitation for these months is shows maxima over the north and west parts, which explains the negative correlation (Fig. 3).

A common characteristic of the $|(E-P)i10<0|$ patterns is that the most intense values are generally located near the moisture sources, as is clear for the contributions from C2, C3, O3, O4, and the CRB itself. The geographic location of the continental sources around the CRB and the dominant atmospheric circulation are the key factors that make this possible.

**3.4** Moisture sources during severe dry and wet periods in the CRB.

We now consider the characteristics of the extreme hydrological conditions seen in the CRB. Central Equatorial Africa (CEA) has experienced a long-term drying trend over the past two decades (Diem et al., 2014, Zhou et al., 2014). The temporal evolution of the 1-, 12- month SPEI series for the CRB, shows dry conditions during the periods: 1980-1985, 1992-

1998 and 2004-2006, approximately (Fig. 112 a, b). The prevalence of wet conditions can be seen from 1985 to 1991 and from 2007 to 2010. In CEA Hua et al. (2016) documented for April-May-June consistently strong negative anomalies falling since the 1990s, primarily related with SST variations over Indo-Pacific associated with the enhanced and westward extended tropical Walker circulation, which is consistent with the weakened ascent over Central Africa associated -with the reduced -low-level moisture transport. Hydrological drought conditions for the Congo River according -to at Kinshasa gauge station records show temporal consistency with climate drought conditions in the basin (Fig. 121-c). Like Mahe et al. (2013) we found that dry years after 1982 were followed by a more humid period.

We calculated the monthly correlations between the anomalies of the total moisture influx to the basin $|(E-P)i10<0|$ (summed from all the sources), runoff, and SSI for the 1- to 24- month SPEI time scales (Figure 12) in order to investigate any possible temporal relationships. The significance of the correlation threshold was set at $p<0.05$. The correlations between monthly values of $|(E-P)i10<0|$ and SPEI show significant and high values for all months (Fig. 12a), recorded for short SPEI time scales. The relationship is positive and statistically significant from January to March within the 24 SPEI time scales. During low rainfall climatological months in the basin, especially in June, July and August the correlations become lowest even negative after the SPEI-4.-5 time scales, and generally remain until the last. It indicates a negative feedback that may reflect the increased evapotranspiration modulating the SPEI. As the months advance and the period of less rain ends, the correlations increase being positive and significant during October - December from first SPEI temporal scales until SPEI-10 approximately. In these months for major SPEI, temporal scales correlations become lowest, being also negative as can be appreciated in Figure 12a. However, it changes for January and February when as commented was found positive correlations at all SPEI time scales. This approximately shows a lag of one month needed for the SPEI to reflect wet condition recovery in the CRB. Although, the lowest values of $|(E-P)i10<0|$ during rainfall decrease months (Fig. 8) and SPEI relationship at different time scales;

In Figure 12b the surface runoff seems to be strongly dependent on precipitation deficit for both shorter and annual rainfall deficit. When the rainfall increases over the basin from July to December (Fig. 8), the correlations also increase. Here we observe the same relationship described before between $|(E-P)i10<0|$ and SPEI; but higher correlations were obtained. Correlations between SSI obtained with Kinshasa gauge station discharge and the SPEI (1–24 months) show that the evolution of hydrological conditions is consistent with the meteorological rainfall deficit state over the basin (Figure 12c). In particular, the strongest and most significant correlations were found with SPEI-5 to -7 from January to May, being maximum in April; this suggests the most appropriate time scales to use when identifying the hydrological drought (according to the Congo River discharge at Kinshasa gauge station) in terms of its relationship with the SPEI computed for the whole CRB. From May to July when the precipitation and discharge are minima (Fig. 3) the correlation is negative at first SPEI temporal scales; suggesting a time response of two or three months to reflect SPEI changes at river discharge.

~~We calculated the monthly correlations between the anomalies of the total moisture influx to the basin $|(E-P)i10<0|$ (summed from all the sources together), runoff, and SSI for the 1- to 24- month SPEI time scales (Figure 13) in order to investigate any possible relationships. The significance of the correlation threshold was set at *p<0.05*. The correlation between $|(E-P)i10<0|$ monthly values and SPEI (Fig. 13a) shows significant and high values for all months, recorded for short SPEI time scales. Figure 13b shows the monthly correlation between the anomalies of runoff and SPEI. During; s. A possible explanation suggest that increased evapotranspiration may modulate the SPEIhigher correlations were obtained. for gauge station records theIn particular, the strongest and most significant correlations were found with SPEI 5 to 7 during April; this suggests the most appropriate time scales to use when identifying the meteorological drought in terms of its relationship with the Congo River discharge at Kinshasa gauge station.are minimum . The relationship is positive and statistically significant from January to April within the 24 SPEI time scales, but it becomes negative when the precipitation decreases over the basin.  Surface runoff seems to be strongly dependent on precipitation deficit for both shorter and annual rainfall deficit. When the rainfall increases over the basin from July to December, the correlation also increases. Correlations between SSI at Kinsasha and SPEI (1-24 months) show that the evolution of hydrological conditions is consistent with the meteorological rainfall deficit state over the basin (Figure 13c). In particular, the strongest and most significant correlations were found with SPEI 5 to 7 during April; this suggests the most appropriate time scales to use when identifying the meteorological drought in terms of its relationship with streamflow in the Congo River discharge at Kinshasa gauge station.~~

To investigate separately the role of the moisture sources during drought and wet conditions in the CRB we selected a few years affected by severe and extreme conditions. For this purpose SPEI values at the 12-month time scale for December were used to diagnose the status of water balance throughout each year. Moreover, long drought time-scales are generally used to assess streamflow droughts (Svoboda et al., 2012). Besides, at this time scale it is appropriate to represent the water balance in a region where the precipitation climatology is dictated by latitudinal migration crossing the Equator over the year, such as occurs in the CRB.

During the period 1980-2010, the years 1995 and 1996 were characterized by severe (SPEI12_December = -1.69) and extreme (SPEI12_December= -2.06) drought conditions respectively, while 1982 is characterized as severely wet (SPEI12_December = 1.68). Fig. 1~~3~~4 shows the mean annual contribution from all sources and the anomaly of $|(E-P)i10<0|$ for each event. In 1982 (Fig.13a) the most important moisture contributions are from the basin itself (~120 mm day$^{-1}$), O3 (~28 mm day$^{-1}$), and C4 (~27 mm day$^{-1}$). The anomalies of $|(E-P)i10<0|$ from all the sources are positive, but it is particularly high for the basin itself (18 mm day$^{-1}$). In 1995 and 1996 (Fig. 13b,c) the greatest moisture loss continues to be that from the air masses from the CRB itself, the oceanic source O3, and the continental C4. However, when the anomalies were analysed all the sources showed negative values, meaning that the moisture support was in fact less than the ~~normal~~ average conditions ~~seen in dry years~~for the whole period. In 1995 the deficit in the contribution from the CRB and O4 is

highlighted. Hua et al. (2016) described how an increase in subsidence across the western edge of Indian Ocean (O4) and a decrease in convection over the Congo Basin (CRB) led to a reduction in moisture transport and rainfall across Central Equatorial Africa. In 1996, a year characterized by extreme drought conditions, the negative anomaly in the moisture supply from all the sources remains, but that computed for the basin is higher than it was in 1995. These results explain a mechanism in which the role of the CRB as moisture source during wet (dry) periods increase (decrease). ~~Therefore, the moisture contribution for the CRB is essentially recycling for the three years considered, and constitutes a key element that modulates the conditions for droughts in the basin via the rainfall~~. ~~To confirm these results, we calculated the spatial anomalies of the moisture losses for air masses tracked from the CRB (Fig. 15). In 1982 (a severe wet year) over the northern half of the basin high positive anomalies of |(E-P)i10<0| values (> 3 mm day⁻¹) occur. For 1995, the anomalies are negative in the~~ west ~~east and north of the basin, and cover almost the whole basin during the extremely dry year (1996).~~

To clarify theses results for the three years under study there was calculated the anomalies of |(E-P)i10<0| (moisture contribution) and (E-P)i10>0 (moisture uptake) in air masses tracked forward and backward in time, repextively, from the CRB. It worth noting that utilizing FLEXPART we obtained the budget of (E-P) but not exactly the recycling which computes the amount of precipitation evaporated falling again within the same region. Besides, to support the results there was calculated the anomaly of the VIMF for every year to check the dynamical conditions favourable to the convergence of moisture flux.

In 1982 a severely wet year, higher positive anomalies of |(E-P)i10<0| are observed in the half north of the CRB, but mostly negative in the south part (Fig. 14a). This pattern is clearly opposite to that obtained for the same year but in the anomalies of (E-P)i10>0 for the backward experiment (Fig. 14d), which explains the strengthening role of the half south of the basin as moisture source; mainly favouring the moisture lose over the north part of the CRB, coinciding with the evergreen forest extends. The anomalies of the VIMF support this result, negative values identifying convergence are appreciated over the half north of the CRB, while positive anomalies indicating divergence in the half south (Fig. 15a). During a wet period is supposed that recycling decrease, however, for the Indian region Pathak et al. (2015) described that whereas the monsoon progresses the enhanced soil moisture and vegetation cover leads to increased evapotranspiration and recycled precipitation. Also for the North American Monsoon region, a positive feedback was previously described by Bosilovich et al. (2003), and Domínguez et al. (2008). In 1982 it may happen that in the half north of the CRB increase both the evaporation and precipitation, but the second much more; thus, affecting the budget of (E-P). It was also documented when the tropical rainbelt shifts northward during boreal summer months; then, the evergreen forest gets active rapidly due to the onset of the rainy season, resulting in the increase of evapotranspiration (Matsuyama et al., 1994).

The Oubangui basin in the northeast of the CRB, should have benefited in 1982 due to positive anomalies of |(E-P)i10<0|, favouring the precipitation in the half north of the CRB. In the Oubangui basin, a decrease in runoff observed everywhere coincides with a decrease in rainfall with a time lag of 3 years, which can be explained by the sponge-like functioning of the drainage basin, where interannual variability is less important for runoff than for the rainfall series (Orange et al., 1997). An

important finding of theses authors is that also the maxima and minima of annual rainfall do not completely coincide with the extreme flow events; as occurred in 1982, a severely wet year when positive anomalies of $|(E-P)i10<0|$ over the half north of the basin including the Oubangui basin. According to the results of Orange et al. (1997), it was documented by Laraque et al. (2013) that from 1982 to 2010 the Oubangui remains in the drought phase, as the Congo returns to a phase of stability.

In 1995 a severely dry year, negative anomalies of $|(E-P)i10<0|$ cover the major part of the basin (Fig. 14b) being more intense over the west and north. Over these areas in the backward analysis are observed positive anomalies of $(E-P)i10>0$ (Fig. 14e) and positive anomalies of the VIMF, indicating the prevalence of divergence (Fig. 15b). In 1996 an extremely dry year, the mechanism is the same like described for 1995 but negative anomalies of $|(E-P)i10<0|$ occupy almost all the basin as well the positive anomalies of $(E-P)i10>0$ does. In the work of Trenberth and Guillemot (1996) are discussed the importance of land surface feedbacks in the 1988 drought and 1993 flood over the United Stated, while results of Dirmeyer and Brubaker, (1999); Bosilovich and Schubert (2001) and Domínguez, et al. (2006) agree that 1988 had a higher recycling ratio than 1993. To resume, in the CRB during dry years 1995 and 1996 prevail positive anomalies of $(E-P)i10>0$; indicating that moisture uptake by the atmosphere predominates. It surely occurs because the evapotranspiration is enhanced and precipitation decrease, but the prevalence of divergence of the VIMF (Fig. 15b,c) does not favour the moisture lose over the basin, which must be transported outside, suggesting the role of the CRB itself as a moisture source for remote regions. A more detailed analysis should be done in future works to determine the role of forests during drought conditions in the CRB. In Figure 12c it's possible to observe, that lowest SSI values obtained for the Kinshasa gauge station discharge data, occur after 1995 and 1996, as commented before due to the lag period from precipitation, runoff and underground water to feed rivers.

In 1995 and 1996 the greatest moisture loss continues to be that from the air masses from the CRB itself, the 15 oceanic source O3,and the continental C4. However, when the anomalies were analysed all the sources showed negative values, meaning that the moisture support was in fact less than the normal conditions seen in dry years. In 1995 the deficit in the contribution from the CRB and O4 is highlighted. Hua et al. (2016) described how an increase in subsidence across the western edge of Indian Ocean (O4) and a decrease in convection over the Congo Basin (CRB) led to a reduction in moisture transport and rainfall across Central Equatorial Africa. In 1996, a year characterized by extreme dought conditions, the 20 negative anomaly in the moisture supply from all the sources remains, but that computed for the basin is higher than it was in 1995.Therefore, the moisture contribution for the CRB is essentially recycling for the three years considered, and constitutes a key element that modulates the conditions for droughts in the basin via the rainfall. To confirm these results, we calculated the spatial anomalies of the moisture losses for air masses tracked from the CRB (Fig. 1). In 1982 (a severe wet year) over the northern half of the basin high positive anomalies of (E-P)i10<0 values (> 3 mm day-1) occur. For 1995, the anomalies are negative in the east and north of the basin, and cover almost the whole basin during the extremely dry year (1996).

An important feature for 1982, 1995 and 1996 is that anomalies of moisture uptake and moisture contribution obtained in air masses tracked backward and forward in time, respectively from the CRB, are not homogenous over the CRB itself. In 1982 and 1995 is best appreciated a relocation of regions sources and sinks of moisture at the basin. This confirms that research on the hydrological cycle should not be developed for the entire basin as a whole, agreeing to Matsuyama et al. (1994). These authors argue that for the CRB the seasonal change of the water budget in the entire basin, can be recognized as the combination of those in the evergreen forest and southern deciduous forest regions, but regional characteristics of the water budget in the basin cannot be explained by studying the basin as a whole.

## 4. Conclusions

The most important climatological moisture sources for the Congo River Basin have been identified using the Lagrangian model FLEXPART, for a 31-year dataset (1980-2010). To assess the relationship between these sources and the hydrological cycle in the basin the relationship with precipitation, runoff and river discharge in at the basin Kinshasa gauging station were all assessed. The mean annual precipitation pattern in the CRB confirms the north-south dipole associated with the annual migration of the ITCZ. On average, maximum rainfall occurs between October and April while minima are observed in June and July, always in good correlation with the runoff and Congo River discharge; in particular the monthly values of discharge have the best correlation ($r$=0.66) with precipitation having a lag of one month, which is the time taken for the runoff to be seen as freshwater in the Congo River. The backward tracking of air masses reveals that the CRB receives humidity from both hemispheres. At an annual scale, four oceanic sources were identified in the Atlantic Ocean, the Indian Ocean and the Red Sea, while the continent contains four sources surrounding the CRB, as well as the basin itself, which acts as its own moisture source. The importance of each source in the moisture uptake of the CRB confirms the main role of the CRB on the negative budgets of (E-P) over the basin itself, representing more than 50% of the total moisture loss over the basin supplied by all sources. Hence local recycling processes are hugely important, as pointed out by other authors. Other important sources providing moisture to the CRB are the tropical Atlantic Ocean (O3) and the continental region in the east of the target area (C4). At the same time, the source O1 located on the Red Sea, despite its high evaporation rate, is considered the least efficient source for providing humidity to the basin. Not only does the efficiency of the sources providing moisture to the CRB depend on the evaporation rate, it also influences the amount of water vapour transported to the basin, making the sources more or less effective in terms of precipitation over the CRB. Indeed, the spatial variability of the patterns of *(E-P)i10<0* over the CRB after tracking the air masses forwards from all the sources confirms the link between the geographical location of the sources and the location of the greatest moisture sinks over the basin, associated with atmospheric circulation. These patterns show a good correlation with precipitation over the basin and demonstratesThese patterns show a good spatial correlation with the precipitation distribution over the basin and demonstrate the ability of FLEXPART to reproduce the temporal and spatial variability of the precipitation over the CRB.

The roles of the sources providing moisture during years with extreme and severe conditions confirm the key role of the CRB in modulating the water balance within itself.

Moreover, it has clearly been shown that dry (wet) periods in the basin are clearly connected with positive negative (negative positive) anomalies of $|(E-P)i10<0|$ P E over in the CRB, mainly in the northern part of the basin. This suggests that during both dry and wet periods, recycling over the basin is of primary importance.. The complex nature of the hydrological feedback mechanisms in the Congo River Basin is now better understood thanks to the identification of the continental and oceanic moisture sources. However, the spatial variability of the $(E-P)$ budget inside the CRB confirm the importance to perform subbasins scale studies to deeply identify the feedbacks of soil-vegetation in the water cycle over the basin.

The results obtained will also support further studies to address the role of these moisture sources during climate extremes such as flooding, droughts, and extreme discharge events in the Congo River, among others. One important aspect for consideration in future research is related to the possible influence of Modes of Climate Variability (such as ENSO, SOI, or QBO) on the modulation of moisture transport from these sources to the CRB.

The roles of the sources providing moisture during years under extreme and severe conditions confirm the key role of the CRB in modulating the water balance within itself. In wet (dry) years the contribution of moisture from the CRB over itself increases (decreases). As average, the water balance in the atmosphere over the CRB is not homogenous in these years, indicating a distinct role within itself. This confirms that research on the hydrological cycle should not be developed for the entire basin as a whole. The Vertically Integrated Moisture Flux (VIMF) divergence inhibit the precipitation during dry years when moisture uptake is enhanced, which suggest the moisture contribution from the CRB to remote regions, an issue to be investigated in future works. To better understand the complex nature of the hydrological feedback mechanisms in the Congo River Basin should be performed the identification of moisture sources for the subbasins of the CRB and determine the role in each one. It would provide more accurate information to understand the precipitation variability and the feedbacks of different soil/forest in the water cycle.

The results here obtained will support further studies to address the role of the CRB moisture sources during climate extremes such as flooding, droughts, and extreme river discharge at this basin. One important aspect for consideration in future research is related to the possible influence of Modes of Climate Variability (such as ENSO, SOI, or QBO) on the modulation of moisture transport from these sources to the CRB.

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**Table 1.** Mean annual Evaporation rate over the sources. Data for the continent were obtained from GLEAM and for the ocean from OAflux.

| _Sources_ | C1 | C2 | C3 | C4 | CRB | O1 | O2 | O3 | O4 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | **Evaporation rate (mm day$^{-1}$)** | | | | | |
| | 1.0 | 2.5 | 1.6 | 1.5 | 2.4 | 4.6 | 1.1 | 0.71 | 4.7 |

**Table 2.** Moisture contribution from the sources to the CRB (%).

| _Sources_ | C1 | C2 | C3 | C4 | CRB | O1 | O2 | O3 | O4 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | **(E-P)i10<0 in %** | | | | | |
| | 2.3 | 6.8 | 2.1 | **12.0** | **59.3** | 0.2 | 1.8 | **11.5** | 4.1 |

15 **Table 3.** Significant monthly correlation (*p<0.05*) between the precipitation from CRU, Runoff from ERA-Int, River discharge from the GRDC and evaporation from GLEAM or OAFLUX, and series of |*(E-P)i10<0*| forward-integrated using FLEXPART from the sources over the CRB, and with the total |*(E-P)i10<0*| amount (T). Period used: 1980 – 2010.

| | **C1** | **C2** | **C3** | **C4** | **CRB** | **O1** | **O2** | **O3** | **O4** | **T** |
|---|---|---|---|---|---|---|---|---|---|---|
| _Evaporation_ | 0.35 | | 0.35 | 0.36 | 0.37 | 0.35 | 0.43 | 0.14 | 0.35 | 0.36 |
| _Precipitation_ | 0.60 | 0.53 | 0.65 | 0.77 | 0.80 | 0.36 | 0.58 | 0.60 | 0.58 | 0.83 |
| _Runoff_ | 0.66 | 0.43 | 0.72 | 0.69 | 0.75 | 0.59 | 0.73 | 0.59 | 0.43 | 0.75 |
| _Discharge_ | 0.49 | | 0.59 | 0.53 | 0.54 | 0.47 | 0.55 | 0.33 | 0.12 | 0.53 |
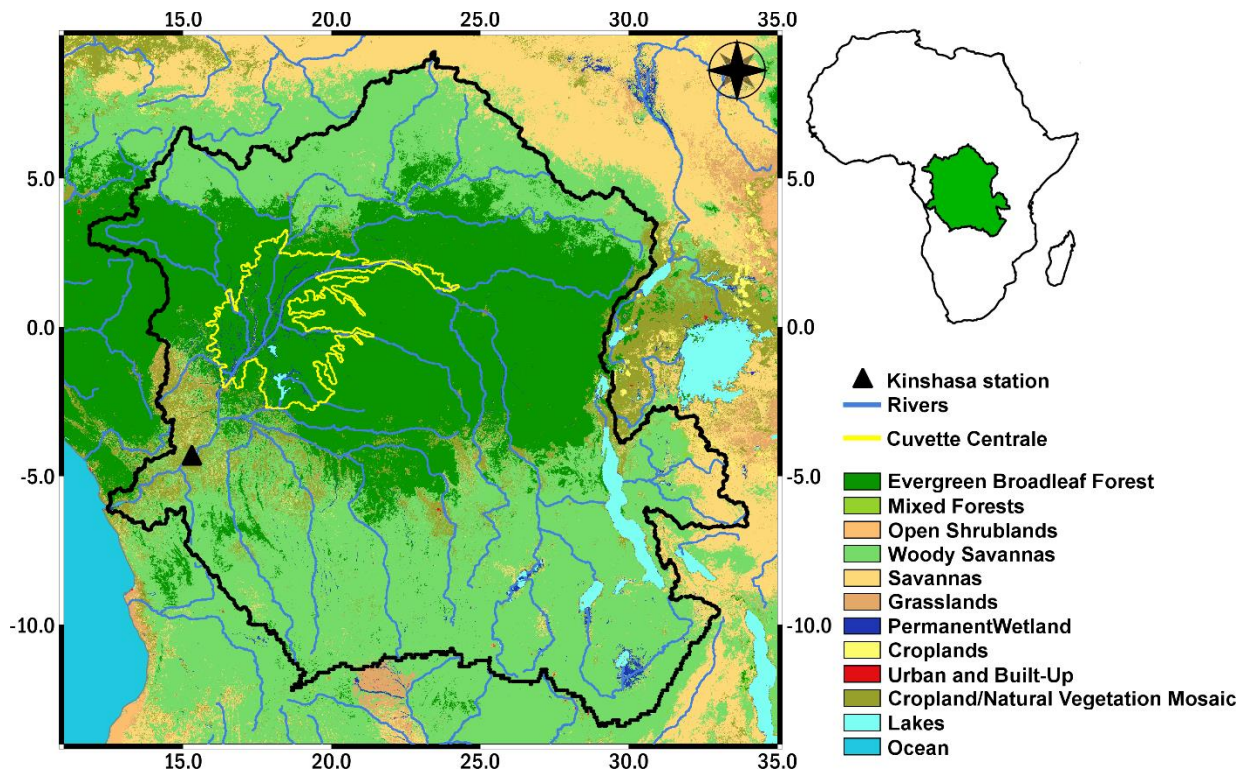
**Figure 1.** Geographic location of the Congo River Basin showing the Kinshasa gauging station, the fluvial system and the land use based on 10 years (2001-2010) (source: Broxton et al., 2014). The boundaries of the Cuvette Centrale is contoured in yellow (adapted from: Betbeter et al., 2014). (source: Hydrosheds project).
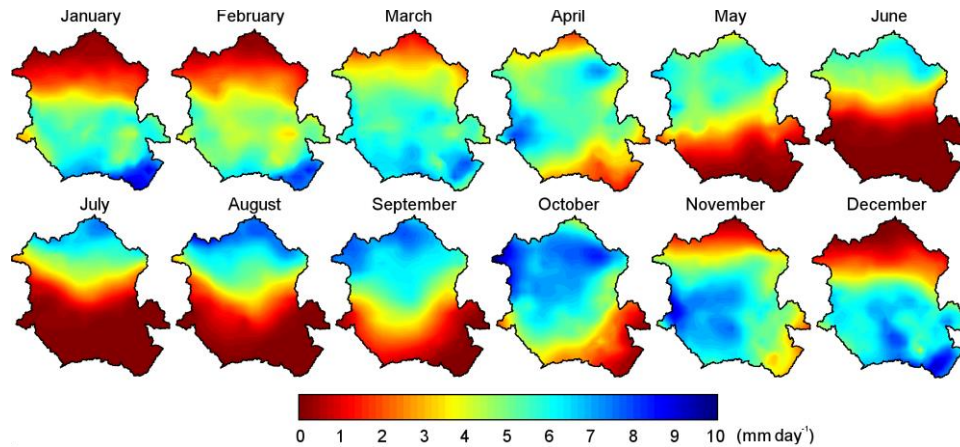
**Figure 2.** Monthly mean precipitation over the CRB for 1980-2010. Data from CRU TS v.3.23.
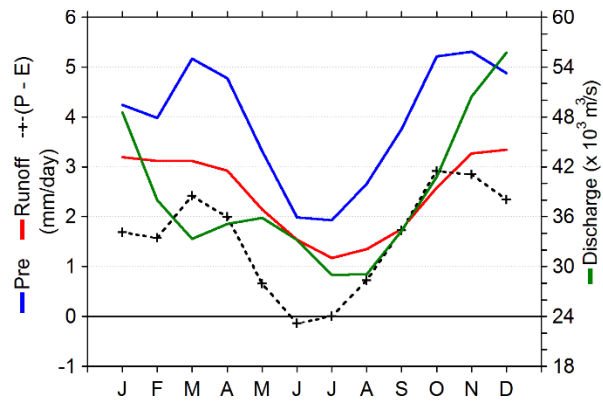
**Figure 3.** Annual cycle of precipitation, runoff and *(P-E)* in the CRB (left axis), and the Congo River discharge (right axis). Data obtained from CRU, ERA-Int, GLEAM and Global Runoff Data Center, respectively.
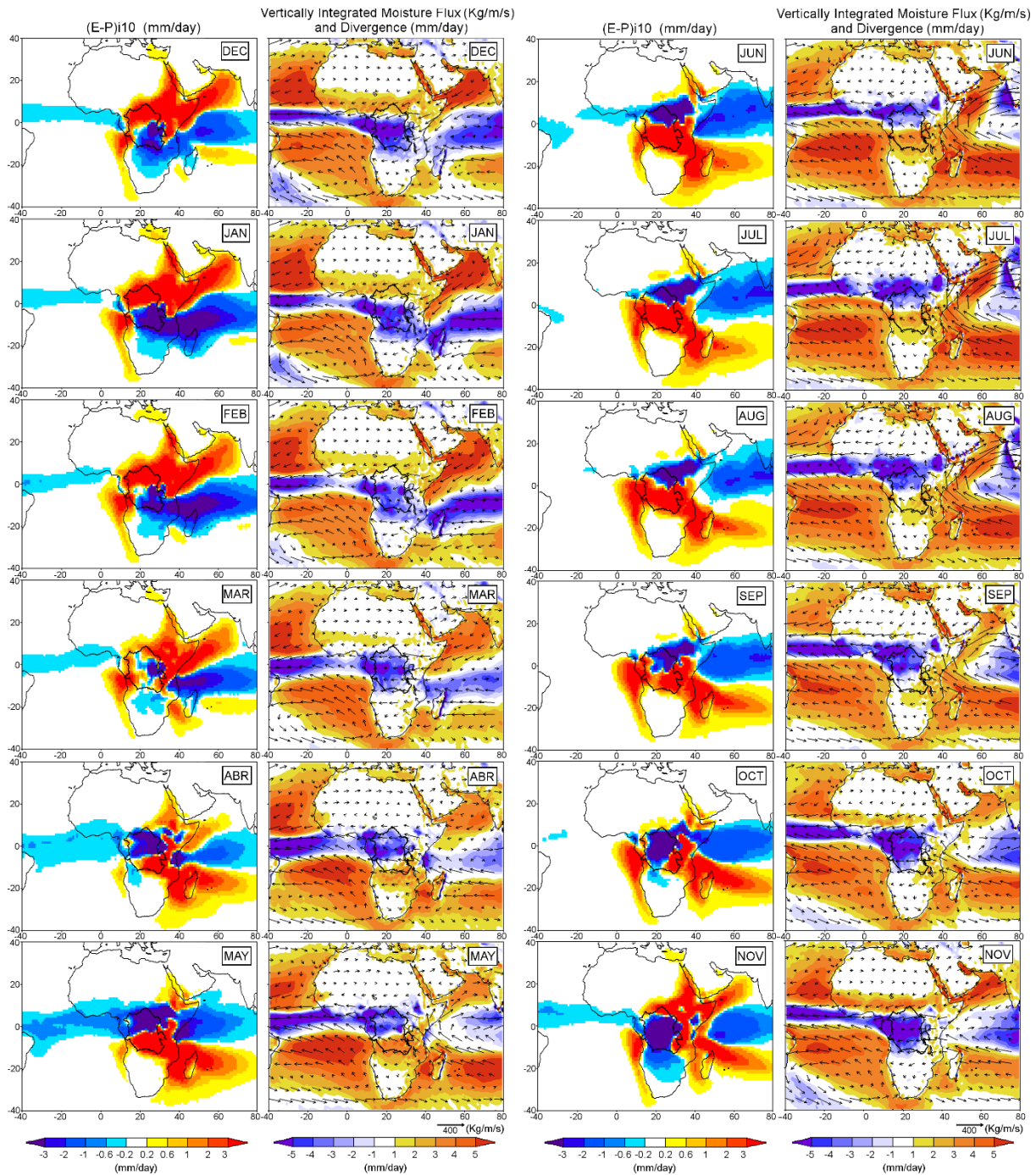
**Figure 4**. Monthly climatological (E-P) values integrated backwards over 10 days (mm day$^{-1}$) alongside Vertically Integrated Moisture Flux (kg/m/s) and divergence-convergence (reddish-blueish colours) (mm day$^{-1}$). Period 1980 - 2010.
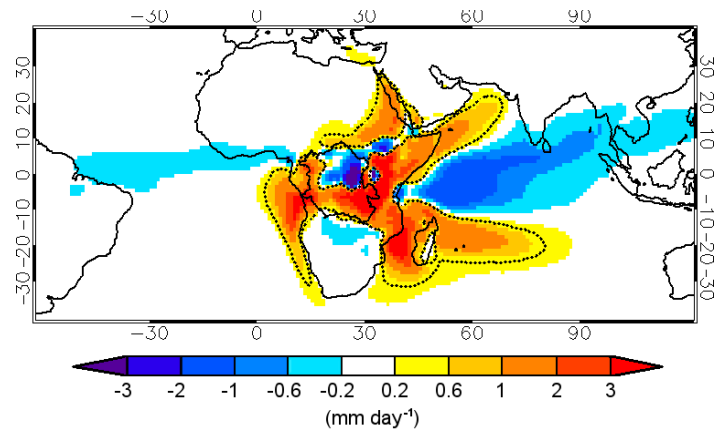
**Figure 5.** Annual mean values of *(E-P)i10* backward-integrated over 10 days for the period 1980-2010. Dashed lines represent the boundaries of the sources of moisture, defined as p90= 0.4 mm day$^{-1}$.
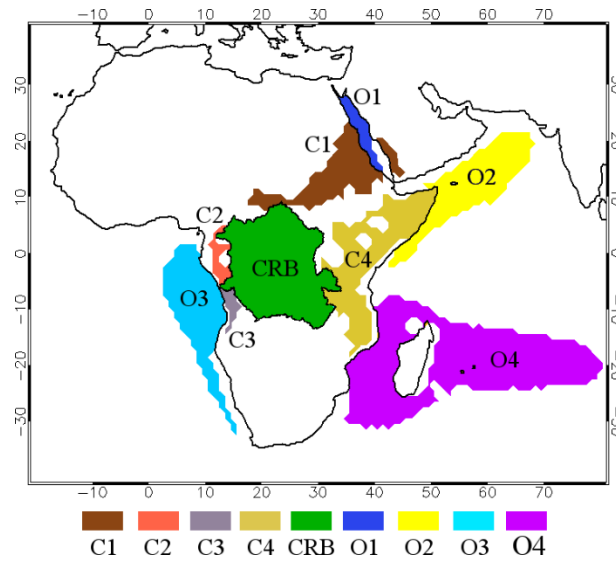
**Figure 6.** Continental moisture sources for CRB: C1, C2, C3, C4, and the CRB itself; Oceanic moisture sources: O1, O2, O3, and O4.
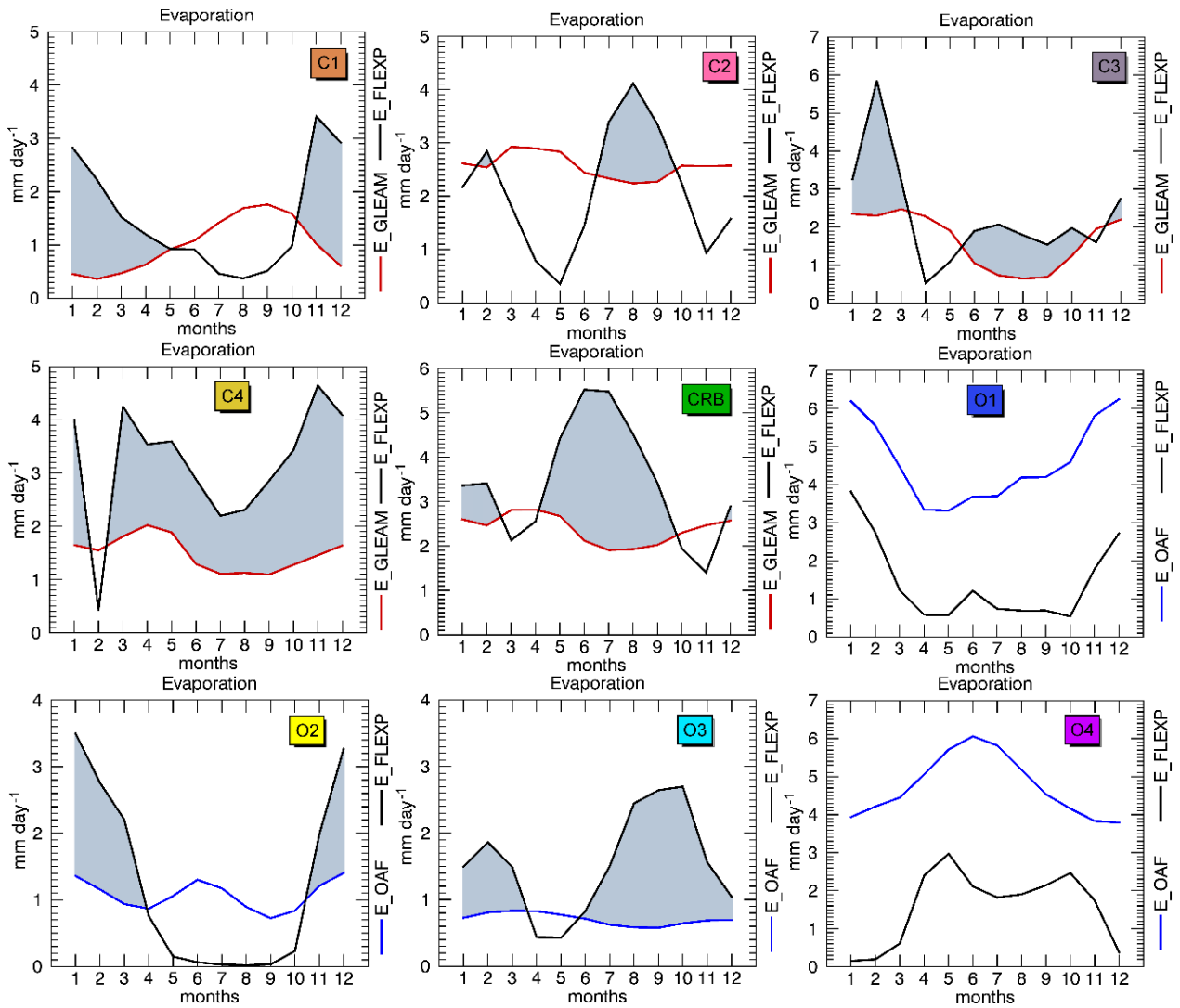
**Figure 7.** Monthly mean evaporation in continental (C) and oceanic (O) sources (in mm day$^{-1}$). Data from GLEAM (red lines) and OAFlux (blue lines). E-FLEX: evaporation values over the sources obtained using FLEXPART (black lines). Areas shaded in gray identify where E-FLEX > Evaporation. Data period: 1980-2010.
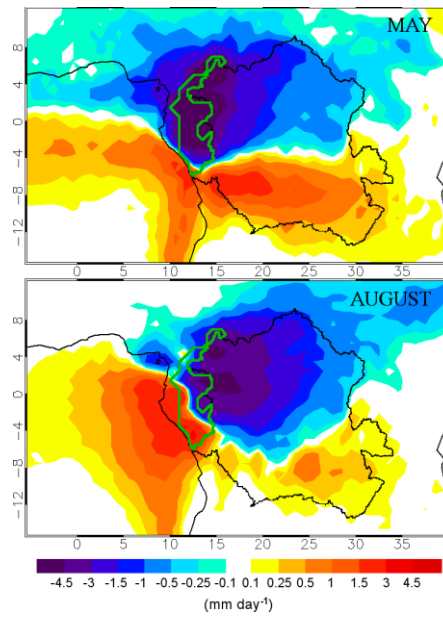
**Figure 8.** Forward *(E-P)*i10 from the moisture source C2 (green contour line) for May (top) and August (bottom). Period 1980-2010.
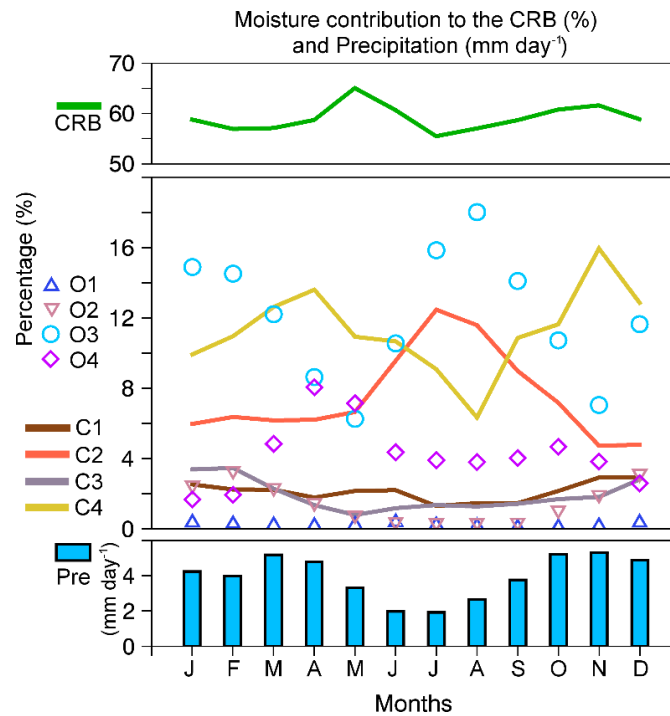
**Figure 89.** Monthly percent of moisture loss calculated as |(E-P)i10<0| forward-integrated from each source over the CRB over 10 days of transport, and monthly mean precipitation from CRU datasets for the period 1980-2010.
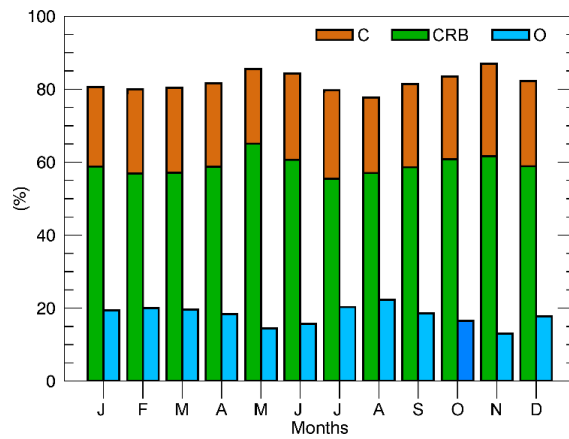
**Figure 910.** Monthly percentage moisture contributions to the CRB from continental sources (red bars), the CRB itself (green bars), and oceanic sources (blue bars). Data from FLEXPART for the period 1980-2010.

$|(E-P)i10<0|$ from:

Continental Sources                    Oceanic Sources

**Figure 1**1~~2~~**.** Time evolution of the SPEI in the Congo River basin at 1 (a), and 12 months (b) and Standardized Streamflow Index (SSI) (c) computed for the Congo River discharge. Period 1980 – 2010.
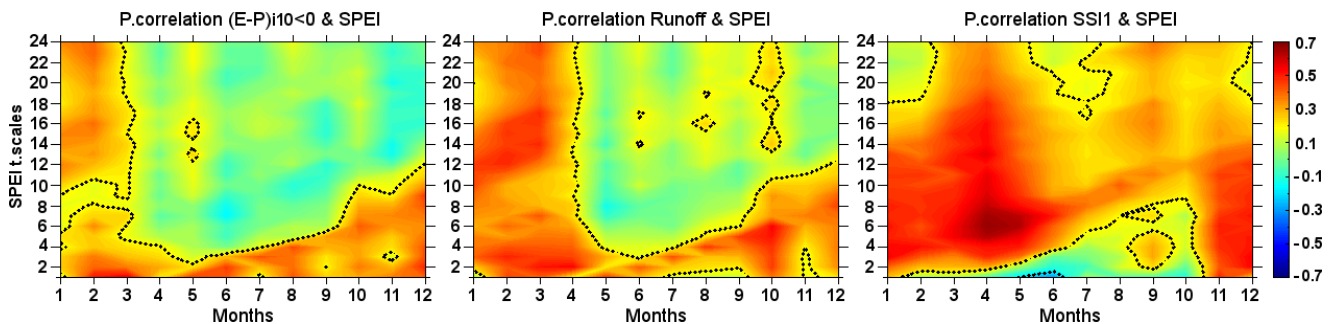
**Figure 1**2~~3~~**.** Monthly correlations between *|(E-P)i10<0|*, runoff and SSI with SPEI-1 to SPEI-24 in the Congo River Basin. Dotted lines represent significant correlations at *p<0.05*.
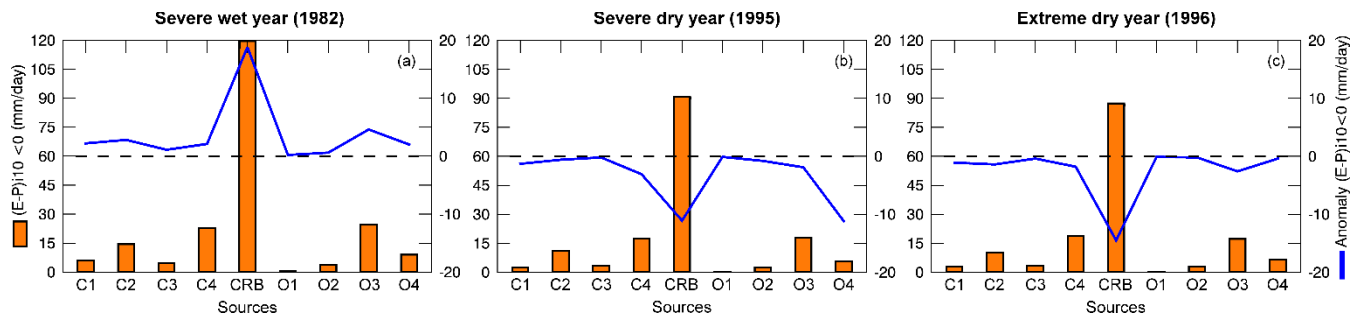
**Figure 1~~3~~4**. Mean annual moisture contribution from the sources to the CRB (orange bars) during 1982 (severe wet conditions, a), 1995 (severe dry conditions, b) and 1996 (extreme dry conditions, c), and the corresponding anomaly (blue line).
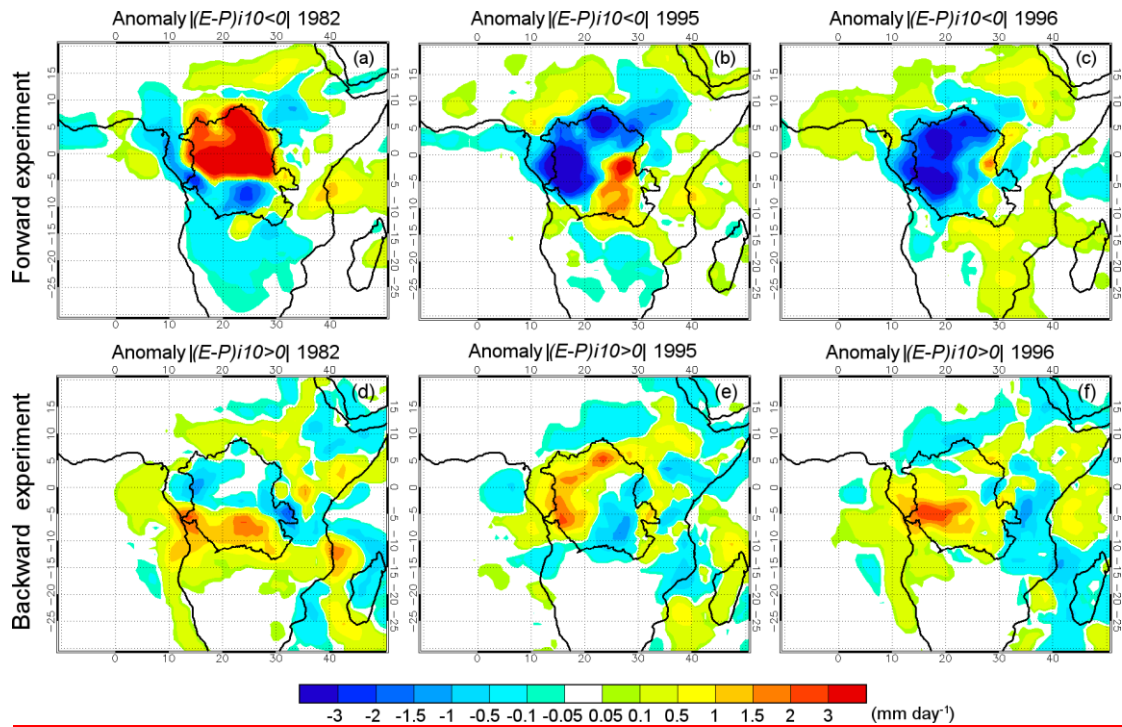
**Figure 1~~4~~5**. Anomaly of the $|(E-P)i10<0|$ (mm day$^{-1}$) integrated forwards from the Congo River basin itself during 1982 (severe wet year, a), 1995 (severe dry year, b) and 1996 (extreme dry year, c). Anomaly of the $|(E-P)i10>0|$ (mm day-1) integrated backwards from the Congo River basin itself during (severe wet year, d), 1995 (severe dry year, e) and 1996 (extreme dry year, f).
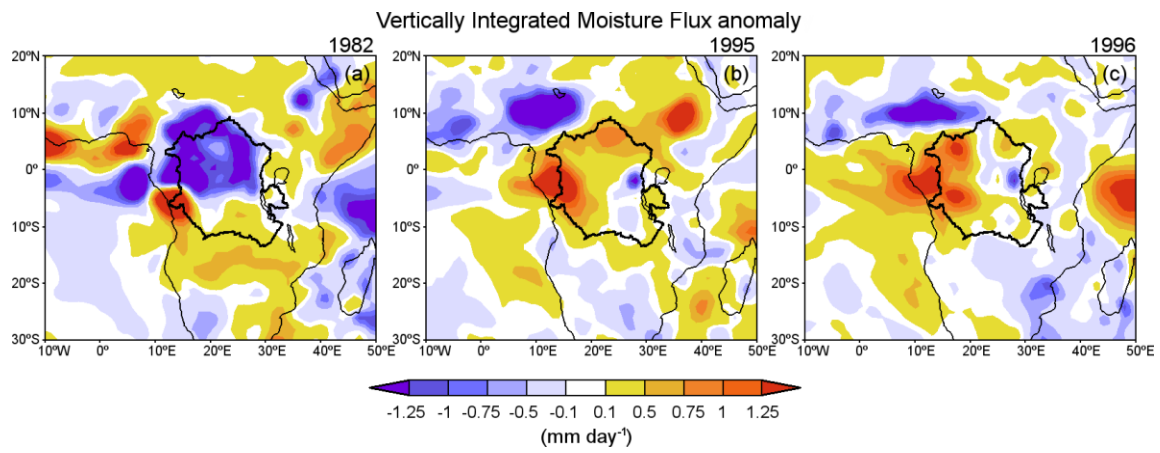
**Figure 1~~65~~5**. Anomaly of the Vertically Integrated Moisture Flux (VIMF) during 1982 (severe wet year, a), 1995 (severe dry year, b) and 1996 (extreme dry year, c).