Contrasting controls on Congo Basin evaporation at the two rainfall peaks

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Abstract

Evaporation is a crucial driver of Congo Basin climate, but the dynamics controlling the seasonality of basin evaporation are not well understood. This study aims to discover why evaporation on the basin-wide average is lower at the November rainfall peak than the March rainfall peak, despite similar rainfall. Using 16-year mean LandFlux-EVAL data, we find that evaporation is lower in November than March in the rainforest and the eastern savannah. The ERA5-Land reanalysis, which effectively reproduces this pattern, shows that transpiration is the main component responsible for lower evaporation in these regions. Using ERA5-Land, we find the following contrasting controls on transpiration, and therefore evaporation, at the two rainfall peaks: (a) In the northern rainforest, there is lower leaf area index (LAI) in November, driven by lower surface downward shortwave radiation (DSR), and lower vapour pressure deficit (VPD) in November, driven by lower sensible heat flux that results from lower net radiation. The combination of lower LAI and VPD explains lower transpiration, and therefore lower evaporation, in November. (b) In the southern rainforest, and in the north-eastern savannah, there is lower LAI in November, driven by lower surface DSR, and this explains lower transpiration, and therefore lower evaporation, in November. (c) In the south-eastern savannah, there is lower LAI in November, driven by lower volumetric water content (VWC), and this explains lower transpiration, and therefore lower evaporation, in November. Collectively, these contrasting controls at the two rainfall peaks explain why the basin-wide average evaporation is lower in November than March.

Keywords Congo Basin · Evaporation · Transpiration · LandFlux-EVAL · ERA5-Land

1 Introduction

The Congo Basin is one of the most convectively active regions of the world, receiving around 1500–2000 mm of rainfall per year (Dezfuli 2017). Over 60% of the rainfall occurs during the wet seasons (Hua et al. 2019), and the basin-wide average seasonal cycle has two rainfall peaks, one in March and the other in November (Crowhurst et al. 2020). Approximately 75% of the rainfall is delivered by mesoscale convective systems (Jackson et al. 2009), which are contiguous areas of cold cloud that exceed 25,000 km² in size (Taylor et al. 2018). A maximum of thunderstorm activity occurs over the eastern Congo Basin, and this region has

one of the highest rainfall totals in the tropics, with an average of 10 mm day⁻¹ delivered during boreal winter (Sandjon et al. 2012). Knowledge of the processes that affect Congo Basin rainfall and its future change is desirable for adaptation planning (Nicholson 2018), as the basin region has a population of more than 75 million people, the majority of whom rely on subsistence agriculture for food and income (Samba and Nganga 2012).

An important factor that affects the seasonality of Congo Basin rainfall which has received little research attention is evaporation from the land surface (Alsdorf et al. 2016). Evaporation is the sum of canopy evaporation, soil evaporation and transpiration (Lawrence et al. 2007). The land surface of the basin, which transitions from a tropical rainforest in the northern half to a deciduous savannah in the southern half, features continually high evaporation throughout the year. This is believed to make a substantial contribution to local rainfall, as evident in high recycling ratios for the basin (Dyer et al. 2017; Sori et al. 2017).

Despite the importance of evaporation for Congo Basin climate, the broad-scale dynamics controlling the seasonality

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of basin evaporation are not well understood. Knowledge of what controls the present-day seasonality of basin evaporation would provide a point of reference with which to compare climate and ecosystem models. This evaluation would determine whether these models produce the correct seasonality of evaporation for the right reasons (Maeda et al. 2017; Adole et al. 2019). Additionally, without a robust understanding of controls on the present-day seasonality, it is difficult to analyse whether model projections of shifts in the seasonality of Congo Basin evaporation are trustworthy (Berg and Sheffield 2019).

1.1 Lower evaporation in November than March in the Congo Basin

Previous studies suggest that although rainfall is likely to be an important control on the seasonal cycle of evaporation in Tropical Africa, other factors could additionally modulate this cycle. For example, in a small region north west of

the basin, Gond et al. (2013) discussed possible controls on the seasonal cycle of enhanced vegetation index (EVI), a variable closely related to evaporation. They argued that the seasonal cycle of EVI is primarily controlled by rainfall, but that light availability is an important secondary control. In this same region, Philippon et al. (2016) argued that there is higher rainfall in the September–October–November (SON) wet season than the March–April–May (MAM) wet season, but lower EVI in SON than MAM. This suggests that factors other than rainfall could modulate EVI during SON.

Averaged across the Congo Basin, Crowhurst et al. (2020) found that the best performing global climate models (GCMs) with low root mean square errors against CHIRPS2 rainfall (Funk et al. 2015) have slightly higher rainfall at the November rainfall peak than the March rainfall peak. While this agrees with several studies (Haensler et al. 2013; Washington et al. 2013; Creese and Washington 2016), and several reanalyses (Fig. 1a, Table 1), the CHIRPS2 data set, which has the best agreement of 10 satellite and gauge

Fig. 1 Sixteen-year mean (1989–2005) seasonal cycles of **a** rainfall (mm day^{-1}) and **b** evaporation (mm day^{-1}) averaged over the Congo Basin (14°S – 4°N , 18°E – 30°E), from four reanalyses, CFSR (Saha et al. 2010), ERA5-Land (Hersbach et al. 2020), MERRA-2 (Gelaro et al. 2017) and NCEP-2 (Kanamitsu et al. 2002), and two reference data sets, CHIRPS2 rainfall (Funk et al. 2015) and LandFlux-EVAL evaporation (Mueller et al. 2013)

Table 1 November minus March rainfall (mm day⁻¹) and evaporation (mm day⁻¹), averaged over the Congo Basin (14° S–4° N, 18° E–30° E) from four reanalysis data sets and two reference data sets

Data set	Data set type	November minus March rainfall (mm day ⁻¹)	November minus March evaporation (mm day ⁻¹)
CFSR (Saha et al. 2010)	Reanalysis	+ 0.25	– 0.34
ERA5-Land (Hersbach et al. 2020)	Reanalysis	+ 0.61	– 0.33
MERRA-2 (Gelaro et al. 2017)	Reanalysis	+ 0.59	– 0.66
NCEP-2 (Kanamitsu et al. 2002)	Reanalysis	+ 1.10	– 0.53
CHIRPS2 rainfall (Funk et al. 2015) and LandFlux-EVAL evaporation (Mueller et al. 2013)	Reference	+ 0.04	– 0.35

rainfall products against the NIC131-Gridded rainfall dataset in the Congo Basin (Nicholson et al. 2019), has a similar amount of rainfall at the two peaks (Fig. 1a, Table 1). This suggests that rainfall amounts on the basin-wide average are similar in March and November. Crowhurst et al. (2020) also found that the best performing GCMs with low root mean square errors against LandFlux-EVAL evaporation reference data (Mueller et al. 2013) have lower evaporation in November than March on the basin-wide average, which agrees with several reanalyses (Fig. 1b, Table 1).

Similar rainfall amounts in March and November suggest that lower water availability is not the cause of lower evaporation in November than March. This similar rainfall also suggests that cloud cover is similar and that lower energy availability is not the cause of lower evaporation either. It therefore remains unclear why evaporation on the basin-wide average is lower at the November rainfall peak than the March rainfall peak, despite similar amounts of rainfall in an equatorial climate. An understanding of the dynamics controlling the seasonality of basin evaporation will only be achieved when factors controlling this difference are revealed.

As evaporation is the sum of three components, a fluctuation in any of these components will cause evaporation to fluctuate (Fisher et al. 2017; Berg and Sheffield 2019). To find out why evaporation is lower in November than March on the basin-wide average, and to begin understanding the controls on the seasonal cycle of basin evaporation, this study will first need to identify where in the basin evaporation is lower in November than March, and then discover which evaporation components are responsible in these regions separately. Crowhurst et al. (2020) found that on the basin-wide average, the best performing GCMs have similar canopy evaporation and soil evaporation in March and November, but lower transpiration in November than March. The authors therefore argued that lower transpiration is likely to explain why evaporation is lower in November than March on the basin-wide average. This result suggests that where evaporation is lower within the basin, lower transpiration could be responsible, although this needs to be verified. Once the relevant evaporation components are identified

regionally, we can then establish contrasting controls on these components at the two rainfall peaks, which cause the components to be reduced in November, and therefore cause the evaporation to be lower in November than March in the identified regions. Collectively, these contrasting controls explain why evaporation is lower at the November rainfall peak than the March rainfall peak on the basin-wide average.

1.2 Aims

To move towards a physical understanding of why Congo Basin evaporation on the basin-wide average is lower at the November rainfall peak than the March rainfall peak, despite similar amounts of rainfall in an equatorial climate, this study aims to:

1. Identify where in the basin lower evaporation in November than March occurs.
2. Discover which evaporation components are responsible for lower evaporation in November than March in the identified regions.
3. Establish contrasting controls on the evaporation components at the two rainfall peaks, which cause the evaporation components to be reduced in November, and therefore cause the evaporation to be lower in November than March in the identified regions.

2 Data and methods

2.1 Domain and evaporation reference data

The studied domain for the Congo Basin is 14° S–4° N, 18° E–30° E (Fig. 2), which covers the evergreen tropical rainforests in the northern half, and the deciduous savannah in the southern half (see Fig. 2 from Yan et al. (2017)). All data sets are averaged over 1989–2005 to produce monthly climatologies. We use LandFlux-EVAL (Mueller et al. 2013) to identify spatially where in the domain lower evaporation in November than March occurs. The main reasons for using LandFlux-EVAL in the absence of in situ evaporation

Fig. 2 Sixteen-year mean (1989–2005) evaporation across Africa (mm day^{-1}) from the LandFlux-EVAL synthesis data set. Congo Basin domain used in this study (14°S – 4°N , 18°E – 30°E) is shown with a red box

observations are that LandFlux-EVAL performed well across the African continent in a water budget evaluation (Weerasinghe et al. 2020), compares favourably against several other products in the basin (Trambauer et al. 2014), and is an ensemble product that does not prioritize use of one algorithm alone (Miralles et al. 2016). Further details are available in Crowhurst et al. (2020).

2.2 Reanalysis data

The LandFlux-EVAL evaporation product does not have data available for the three evaporation components. Therefore, we use a reanalysis which does produce this data to discover which evaporation components are responsible for lower evaporation in November than March within the basin. Reanalyses assimilate observations with a numerical model to generate a dynamically consistent, gridded estimate of the climate system (Parker 2016). They are useful tools that

can help understand climate dynamics in data-scarce parts of the world (Hua et al. 2019). However, as there is little agreement between reanalyses on their simulation of the hydrological cycle in the Congo Basin (Washington et al. 2013; Maidment et al. 2015), it is necessary to find a reanalysis which effectively reproduces the evaporation difference between March and November from LandFlux-EVAL. Good agreement would indicate that a reanalysis is deriving the evaporation difference using a realistic set of processes. This would allow us to trust how the reanalysis partitions the evaporation difference into its three components, and then use this reanalysis to establish reasons why specific evaporation components are lower in November than March in the different regions of the basin.

We use three criteria to determine whether a reanalysis is suitable for evaluation against LandFlux-EVAL: (1) the reanalysis is the latest version available of its type, (2) the reanalysis is fully independent from LandFlux-EVAL, which allows for a fair comparison, and (3) data for evaporation, its three components, and a variety of evaporation drivers are available from the reanalysis. To the knowledge of the authors, ERA5-Land and MERRA-2 are the only reanalyses that meet these criteria (Mueller et al. 2013; Schwingshackl et al. 2017). Further details on LandFlux-EVAL and the two reanalyses to be evaluated are described in Table 2.

2.3 Methods

We first produce a climatological November minus March evaporation difference map for LandFlux-EVAL by calculating the spatial distribution of LandFlux-EVAL evaporation for March and November for the studied domain, and subtracting the March distribution from the November distribution. The resulting difference map allows us to identify the regions of the basin with lower evaporation in November than March. We then produce a November minus March evaporation difference map for the ERA5-Land and MERRA-2 reanalyses, and select the reanalysis which most effectively reproduces LandFlux-EVAL.

Using the selected reanalysis, we produce November minus March difference maps for canopy evaporation, soil evaporation and transpiration, and discover which of the

Table 2 Further details on LandFlux-EVAL and the two reanalyses evaluated in this study

Data set	Spatial resolution	Temporal resolution	Available periods	Land surface model
LandFlux-EVAL (Mueller et al. 2013)	$1.0^{\circ} \times 1.0^{\circ}$	Monthly	1989–2005	LandFlux-EVAL Synthesis Algorithm (Mueller et al. 2013)
MERRA-2 (Gelaro et al. 2017)	$0.5^{\circ} \times 0.625^{\circ}$	Monthly	1980–2008	MERRA-2 Catchment Model (Reichle et al. 2017)
ERA5-Land (Hersbach et al. 2020)	$0.1^{\circ} \times 0.1^{\circ}$	Monthly	1981–2020	H-TESSSEL (Balsamo et al. 2009)

Monthly climatologies are produced by averaging over 1989–2005 for all data sets

evaporation components are responsible for lower evaporation in November than March in the basin regions identified from LandFlux-EVAL. We then produce November minus March difference maps for a range of possible controls on these particular components. This allows us to determine the contrasting controls which cause these components to be reduced in November, and therefore cause evaporation to be lower in November than March in the basin regions identified from LandFlux-EVAL. Methods used to derive each of the controls are listed in the Appendix.

The robustness of the difference between the March and November values is assessed on each difference map using the double-sided Students t-test. Regions of stippling indicate where the mean difference between March and November is statistically significant ($p < 0.05$).

3 Lower evaporation in November than March

3.1 Regions

Figure 3a shows the November minus March evaporation difference map produced by LandFlux-EVAL. There is lower evaporation in November than March in two regions: (1) the rainforest, with coordinates 4°S – 2°N , 18°E – 30°E and a regional mean difference of -0.25 mm day^{-1} , and (2) the eastern savannah, with coordinates 14°S – 4°S , 24°E – 30°E and a regional mean difference of -0.60 mm day^{-1} . As the processes controlling evaporation might be influenced by vegetation type, we analyse these two regions separately in the rest of the study.

Fig. 3 Sixteen-year mean (1989–2005) November minus March evaporation (mm day^{-1}) difference maps from **a** LandFlux-EVAL, **b** ERA5-Land, and **c** MERRA-2. The domain used in this study (14°S – 4°N , 18°E – 30°E) is shown with a red box. Sub-domains are shown with blue boxes and indicate the two regions in LandFlux-EVAL where evaporation is lower in November than March: (1) the rainforest, and (2) the eastern savannah. Dots are grid points where the difference between March and November is statistically significant ($p < 0.05$)

3.2 ERA5-Land v MERRA-2

We now discuss whether ERA5-Land or MERRA-2 should be used to discover which components are responsible for lower evaporation in November than March in the rainforest and the eastern savannah. Figure 3b shows the November minus March evaporation difference map produced by ERA5-Land. This reanalysis does effectively reproduce the pattern of lower evaporation in November than March in the rainforest and the eastern savannah that is evident in LandFlux-EVAL (Fig. 3a). Even though in the eastern rainforest (coordinates 4° S–2° N, 24° E–30° E), regional mean evaporation in ERA5-Land is 0.45 mm day⁻¹ lower in November than March, as opposed to 0.30 mm day⁻¹ for LandFlux-EVAL, this small discrepancy is too insignificant to rule out ERA5-Land as a preferred reanalysis.

Figure 3c shows the November minus March evaporation difference map produced by MERRA-2. This reanalysis does not effectively reproduce the pattern of lower evaporation in November than March in the rainforest and the eastern savannah evident in LandFlux-EVAL (Fig. 3a). In the eastern rainforest (coordinates 4° S–2° N, 24° E–30° E), regional mean evaporation in MERRA-2 is 0.80 mm day⁻¹ lower in November than March, as opposed to 0.30 mm day⁻¹ for LandFlux-EVAL. In the eastern savannah, regional mean evaporation in MERRA-2 is 0.90 mm day⁻¹ lower in November than March, as opposed to 0.60 mm day⁻¹ for LandFlux-EVAL. These two discrepancies rule out the further use of MERRA-2 in this study.

The good agreement between LandFlux-EVAL and ERA5-Land suggests that the ERA5-Land reanalysis is deriving the evaporation difference between March and November using a realistic set of processes. Therefore, we use ERA5-Land data to discover the evaporation components responsible for lower evaporation in November than March in the rainforest and the eastern savannah.

3.3 Rainforest

Figure 4 shows the November minus March canopy evaporation (Fig. 4a), soil evaporation (Fig. 4b), and transpiration (Fig. 4c), difference maps produced by ERA5-Land. In the rainforest, regional mean evaporation in ERA5-Land is 0.35 mm day⁻¹ lower in November than March (Fig. 3b). This is partitioned into 0.26 mm day⁻¹ higher canopy evaporation (Fig. 4a), 0.02 mm day⁻¹ lower soil evaporation (Fig. 4b) and 0.59 mm day⁻¹ lower transpiration (Fig. 4c). In ERA5-Land, lower transpiration is 97% responsible for lower evaporation in November than March, with 3% explained by lower soil evaporation. On the regional mean, transpiration is therefore the main component responsible for lower evaporation in November than March in the rainforest. However, higher canopy evaporation in November than March offsets lower

transpiration, thereby reducing the amplitude of the evaporation difference.

At every grid point within the rainforest, Fig. 4 shows that lower transpiration is almost fully responsible for lower evaporation in November than March, with soil evaporation explaining the very small remainder. There are some hotspots where the transpiration difference between March and November is much larger than the regional mean. The most prominent is at the 2° S, 28° E coordinate, where transpiration is 0.85 mm day⁻¹ lower in November than March.

3.4 Eastern savannah

In the eastern savannah, regional mean evaporation in ERA5-Land is 0.53 mm day⁻¹ lower in November than March (Fig. 3b). This is partitioned into 0.02 mm day⁻¹ higher canopy evaporation (Fig. 4a), 0.01 mm day⁻¹ higher soil evaporation (Fig. 4b) and 0.57 mm day⁻¹ lower transpiration (Fig. 4c). On the regional mean, transpiration is therefore the only component responsible for lower evaporation in November than March in the eastern savannah. An interesting observation is that the offsetting of lower transpiration in November by higher canopy evaporation does not occur in the eastern savannah. This explains why the evaporation difference between March and November is larger in the eastern savannah (– 0.53 mm day⁻¹) than in the rainforest (– 0.35 mm day⁻¹) on the regional mean.

Figure 4 shows that the partitioning of the evaporation difference into its components varies within the eastern savannah. In the north-eastern savannah, coordinates 9° S–4° S, 24° E–30° E, regional mean evaporation in ERA5-Land is 0.37 mm day⁻¹ lower in November than March (Fig. 3b), because canopy evaporation is 0.16 mm day⁻¹ higher, soil evaporation is 0.02 mm day⁻¹ lower and transpiration is 0.51 mm day⁻¹ lower (Fig. 4). Lower transpiration is therefore responsible for 96% of the lower evaporation in November than March, with 4% explained by lower soil evaporation. In the south-eastern savannah, coordinates 14° S–9° S, 24° E–30° E, regional mean evaporation in ERA5-Land is 0.66 mm day⁻¹ lower in November than March (Fig. 3b) because canopy evaporation is 0.12 mm day⁻¹ lower, soil evaporation is 0.03 mm day⁻¹ higher and transpiration is 0.57 mm day⁻¹ lower (Fig. 4). Lower transpiration is therefore responsible for 83% of the lower evaporation in November than March, with 17% explained by lower canopy evaporation.

4 Contrasting controls on transpiration at the two rainfall peaks

As transpiration is largely responsible for the lower evaporation, we now use ERA5-Land to establish the contrasting controls on transpiration at the two rainfall peaks of

Fig. 4 Sixteen-year mean (1989–2005) **a** November minus March canopy evaporation (mm day^{-1}), **b** November minus March soil evaporation (mm day^{-1}), and **c** November minus March transpiration (mm day^{-1}), difference maps from ERA5-Land. Domains are as for Fig. 3. Dots are grid points where the difference between March and November is statistically significant ($p < 0.05$)

March and November. These cause transpiration to be reduced in November, and therefore lower the evaporation in November compared to March in the rainforest and the eastern savannah. Collectively, these contrasting controls explain why evaporation is lower in November than March on the basin-wide average. To establish these contrasting controls, we produce November minus March difference maps for possible controls on the lower transpiration, and then discuss whether the contrasts in these controls are sufficient to explain the lower transpiration. If they are sufficient, we then suggest what causes these controls to differ between March and November.

4.1 Leaf area index (LAI) and vapour pressure deficit (VPD)

Although several drivers interact to control transpiration variability, studies confirm that leaf area index (LAI), or the one-sided leaf area per unit ground area, is the main control on transpiration at a global scale (Lian et al. 2018). Lower LAI typically means that there are fewer stomata, which results in lower water supply through transpiration (Wei et al. 2017). Another variable which may contribute to the lower transpiration is lower vapour pressure deficit (VPD), defined as the atmospheric demand that provides

the driving force for transpiration (Massmann et al. 2019). Given that VPD is believed to have implications for land surface processes in the Amazon (Barkhordarian et al. 2019), VPD could also be important in the Congo. Lower VPD typically means that the atmospheric demand for evaporation is lower, and so less water moves through the stem and transpires through the stomata (Bonal et al. 2016).

Figure 5 shows the November minus March LAI (Fig. 5a) and VPD (Fig. 5b) difference maps produced by ERA5-Land. The derivation of LAI is presented in Appendix 1, and the derivation of VPD is presented in Appendix 2. In the rainforest, there are variations in the LAI and VPD differences between the northern and southern rainforest, while in the eastern savannah, there is variation in the VPD difference between the north-eastern and south-eastern savannah. We therefore sub-divide the two regions of lower evaporation into northern and southern halves, as indicated on Fig. 5, and analyse these four sub-domains separately.

The differences in VPD between March and November in the southern rainforest (-0.06 kPa) and the north-eastern savannah (-0.02 kPa) are very small (Fig. 5b) and do not contribute to the lower transpiration in November than March. Lower LAI alone is therefore likely to explain the lower November transpiration in these parts of the basin (Fig. 5a). In the southern rainforest, where VPD is not an important control, the $\Delta\text{LAI}/\Delta\text{Transpiration}$ ratio is approximately 1.0. This indicates that where LAI is 1 unit lower, transpiration is 1 mm day^{-1} lower. As the northern rainforest and southern rainforest are of identical vegetation type, the $\Delta\text{LAI}/\Delta\text{Transpiration}$ ratio of 1.0 applies to the northern rainforest too. Figure 5a shows that there is $0.18 \text{ m}^2 \text{ m}^{-2}$ lower LAI in November than March in the northern rainforest, which implies that there should be 0.18 mm day^{-1} lower transpiration in November than March. However,

transpiration is 0.46 mm day^{-1} lower in November than March (Fig. 4c). This indicates that another variable further lowers the transpiration difference in the northern rainforest in November. In this region, VPD is 0.17 kPa lower in November than March (Fig. 5b), and the combination of $0.18 \text{ m}^2 \text{ m}^{-2}$ lower LAI and 0.17 kPa lower VPD offers a full explanation for the 0.46 mm day^{-1} lower transpiration in November than March in ERA5-Land.

In the south-eastern savannah, VPD is 0.39 kPa higher in November than March (Fig. 5b). This causes higher evaporative demand, which should theoretically lead to higher transpiration. However, the down-regulation of transpiration in November compared to March suggests that the effect of the lower LAI (Fig. 5a) outweighs the effect of the higher VPD (Fig. 5b), and that the lower LAI explains the lower transpiration.

4.2 Causes of lower LAI in November than March

LAI is controlled by water or light availability (Cwiling and Field 2003; Myneni et al. 2007). We therefore calculate November minus March difference maps for soil moisture and solar radiation, and discuss whether lower water or light availability is able to explain lower LAI in November than March in the four sub-domains.

The measure of soil moisture we use is one metre volumetric water content (VWC), which is the percentage of wet soil mass compared to total soil mass. The derivation of one metre VWC from ERA5-Land data is presented in Appendix 3. Figure 6 shows the November minus March VWC difference map produced by ERA5-Land (Fig. 6a), as well as water budget diagrams for the four parts of the basin (Fig. 6b–e). These diagrams allow us to determine why VWC differs between March and November in ERA5-Land.

Fig. 5 Sixteen-year mean (1989–2005) **a** November minus March leaf area index ($\text{m}^2 \text{ m}^{-2}$), and **b** November minus March vapour pressure deficit (kPa), difference maps from ERA5-Land. Domains are as for Fig. 3, with additional sub-division into the northern rainforest, southern rainforest, north-eastern savannah and south-eastern savannah. Dots are grid points where the difference between March and November is statistically significant ($p < 0.05$)

Fig. 6 **a** Sixteen-year mean (1989–2005) November minus March volumetric water content (%) difference map from ERA5-Land, where domains are as for Fig. 5, and dots are grid points where the difference between March and November is statistically significant ($p < 0.05$). **b–e** Sixteen-year mean (1989–2005) water budget diagrams from ERA5-Land for **b** the northern rainforest, **c** the southern rainforest, **d** the north-eastern savannah, and **e** the south-eastern savannah

The measure of solar radiation we use is surface downward shortwave radiation (DSR). This variable is available directly from ERA5-Land. November minus March difference maps are presented for surface DSR (Fig. 7a) as well as the decomposition into its three components: (1) top-of-atmosphere (TOA) DSR (Fig. 7b) + (2) the reduction in surface DSR due to cloud cover ('cloud forcing') (Fig. 7c) + (3) the reduction in surface DSR due to atmospheric absorption ('atmospheric forcing') (Fig. 7d). The derivation of these components from ERA5-Land data is presented in Appendix 4. These difference maps allow us to determine why surface DSR differs between March and November in the ERA5-Land reanalysis.

4.2.1 Northern rainforest

In the northern rainforest, VWC is 7% higher in November than March, with values of 35% in March and 42% in November (Fig. 6a). Higher VWC in November than March occurs due to soil moisture accumulation between March and May and between July and November, which outweighs soil moisture depletion between May and July (Fig. 6b). The higher water availability in November than March cannot explain why LAI is lower in November than March. The typical field capacity of the clay soil in the basin is between 45 and 55%, so the soil in November is close to saturation (Van Engelen et al. 2013) and water availability is not a control on leaf growth. Instead, light availability controls leaf growth as the soil moisture content is high.

Fig. 7 Sixteen-year mean (1989–2005) **a** November minus March surface DSR (W m^{-2}), **b** November minus March top-of-atmosphere DSR (W m^{-2}), **c** November minus March cloud forcing (W m^{-2}), and **d** November minus March atmospheric forcing (W m^{-2}), difference maps from ERA5-Land. Domains are as for Fig. 5. Dots are grid points where the difference between March and November is statistically significant ($p < 0.05$). **a** is equal to **b** + **c** + **d**

There is 26 W m^{-2} lower surface DSR in November than March (Fig. 7a). This is the sum of 18 W m^{-2} less TOA DSR (Fig. 7b), 12 W m^{-2} less surface DSR due to higher cloud cover (Fig. 7c), and 4 W m^{-2} more surface DSR due to lower atmospheric absorption (Fig. 7d). Therefore, the lower surface DSR, caused by lower TOA DSR and higher cloud cover, explains why LAI is $0.18 \text{ m}^2 \text{ m}^{-2}$ lower in November than March (Fig. 5a).

4.2.2 Southern rainforest

In the southern rainforest, VWC is 4% higher in November than March, with values of 37% in March and 41% in November (Fig. 6a). The lower percentage difference in the southern rainforest compared to the northern rainforest is due to a larger soil moisture depletion between May and August (Fig. 6c). Higher water availability in November than March cannot explain why LAI is lower in November than March. The soil is close to saturation in November, and light availability controls LAI. There is 17 W m^{-2} lower surface DSR in November than March (Fig. 7a). This is the sum of 8 W m^{-2} less TOA DSR (Fig. 7b), 10 W m^{-2} less surface DSR due to higher cloud cover (Fig. 7c), and 1 W m^{-2} more surface DSR due to lower atmospheric absorption (Fig. 7d). Therefore, the lower surface DSR, caused by lower TOA DSR and higher cloud cover, explains why LAI is $0.55 \text{ m}^2 \text{ m}^{-2}$ lower in November than March (Fig. 5a). This effect is particularly strong at the 2°S , 28°E hotspot (Figs. 4c, 5a) and this may be due to the influence of mesoscale convective systems, which develop in the afternoon in November and block incoming sunlight. This hotspot of convective activity is not present in March (Jackson et al. 2009; Hart et al. 2019).

4.2.3 North-eastern savannah

In the north-eastern savannah, VWC is 4% lower in November than March, with values of 41% in March and 37% in November (Fig. 6a). Lower VWC occurs due to soil moisture depletion between March and September, which outweighs soil moisture accumulation between September and November (Fig. 6d). Although lower VWC does covary with lower LAI, the soil is close to saturation in November, and light availability still controls LAI. There is 10 W m^{-2} lower surface DSR in November than March (Fig. 7a). This

is the sum of 8 W m^{-2} higher TOA DSR (Fig. 7b), 15 W m^{-2} less DSR due to higher cloud cover (Fig. 7c), and 3 W m^{-2} less DSR due to higher atmospheric absorption (Fig. 7d). Therefore lower surface DSR, caused by higher cloud cover, explains why LAI is $0.35 \text{ m}^2 \text{ m}^{-2}$ lower in November than March (Fig. 5a).

4.2.4 South-eastern savannah

In the south-eastern savannah, VWC is 15% lower in November than March, with values of 42% in March and 27% in November (Fig. 6a). This occurs because a large soil moisture depletion between March and October outweighs a small recovery in soil moisture between October and November (Fig. 6e). There is 25 W m^{-2} higher surface DSR in November than March (Fig. 7a). This is the sum of 25 W m^{-2} higher TOA DSR (Fig. 7b), 5 W m^{-2} less DSR due to higher cloud cover (Fig. 7c), and 5 W m^{-2} more DSR due to lower atmospheric absorption (Fig. 7d). However, higher light availability cannot cause lower LAI in November than March. Instead, lower VWC in November, driven by soil moisture depletion between March and October, is the limiting factor and explains why LAI is $0.44 \text{ m}^2 \text{ m}^{-2}$ lower in November than March (Fig. 5a).

4.3 Cause of lower VPD in November than March in the northern rainforest

As lower VPD contributes to lower transpiration in the northern rainforest, we investigate the factors that cause lower VPD in this region. VPD is defined as the saturated vapour pressure (SVP) minus the actual vapour pressure (AVP). SVP is a function of air temperature, while AVP is a function of specific humidity. SVP is 0.23 kPa lower and AVP is 0.06 kPa lower in November than March in the northern rainforest. This indicates that lower VPD in November than March is predominately a result of lower temperature rather than lower humidity.

Table 3 shows differences in the surface energy budget between March and November in the northern rainforest. Surface net radiation is 15 W m^{-2} lower in November than March, meaning that less net radiation is absorbed by the leaves at the top of the rainforest canopy. These leaves release 6 W m^{-2} less sensible heat flux, which explains why

Table 3 Sixteen-year mean (1989–2005) November minus March surface energy budget averaged over the northern rainforest (2°S – 1°N , 18°E – 30°E) from ERA5-Land

Downward flux	November minus March value (W m^{-2})	Upward flux	November minus March value (W m^{-2})
Net Radiation (NR)	– 15.21	Sensible heat flux (SHF)	– 5.47
Ground Heat Flux (G)	– 0.41	Latent heat flux (LHF)	– 9.33
Total (NR – G)	– 14.80	Total (SHF + LHF)	– 14.80

the near-surface atmosphere is 1.15 °C cooler. This in turn explains why SVP is 0.23 kPa lower in November.

As described in Sects. 4.1 and 4.2, lower surface DSR causes lower LAI, which in turn lowers transpiration in the northern rainforest. This lower transpiration means that specific humidity and AVP are lower, which causes higher VPD (as $SVP - (-AVP) = +VPD$). However, as described in the previous paragraph, lower surface net radiation causes lower sensible heat flux from the leaves, which in turn lowers the near-surface air temperature, SVP and VPD. The net result is that VPD is lower in November than March, and this further lowers the transpiration difference to its final value of $-0.46 \text{ mm day}^{-1}$ (Fig. 4c). The lower transpiration means that latent heat flux is 9 W m^{-2} lower in November than March (Table 3), and the energy budget therefore maintains its balance in November. This is because the lower net radiation in November balances the lower sensible heat flux and lower latent heat flux.

5 Summary and discussion

Using LandFlux-EVAL, this study has found that evaporation is lower in November than March in two regions of the basin, the rainforest and the eastern savannah. To determine which components are responsible for the lower evaporation in these regions, ERA5-Land was used because it effectively reproduces the pattern of lower evaporation in November than March evident in LandFlux-EVAL. The good agreement between LandFlux-EVAL and ERA5-Land suggests that ERA5-Land is deriving the evaporation difference between March and November using a realistic set of processes. Therefore, using ERA5-Land, this study has found that the transpiration component of evaporation is the main component responsible for lower evaporation in November than March in these two regions.

5.1 Contrasting controls on Congo Basin evaporation at the two rainfall peaks

We used ERA5-Land to establish the contrasting controls on transpiration at the two rainfall peaks. These contrasting controls cause transpiration to be reduced in November, and therefore lower the evaporation in November compared to March in the rainforest and the eastern savannah. To find these contrasting controls, we produced November minus March difference maps for possible controls on the lower transpiration, discussed whether the contrasts in these controls are sufficient to explain the lower transpiration, and suggested what causes these controls to differ between March and November. Although many drivers

affect transpiration, this study has analysed supply (LAI) and demand (VPD) controls which are recognised globally as two of the most important (Lian et al. 2018; Barkhordarian et al. 2019). The regional variations in these contrasting controls are summarised below and visualised in Fig. 8.

1. In the northern rainforest, there is lower LAI in November than March. This is driven by lower surface DSR in November, which is a response to lower TOA DSR and higher cloud cover. Additionally, there is lower VPD in November than March. This is driven by lower net radiation in November. As less net radiation is absorbed by the leaves, the leaves emit less sensible heat. The result is a cooler near-surface air temperature, lower SVP and lower VPD. The combination of lower LAI and lower VPD explains lower transpiration, and therefore lower evaporation, in November than March.
2. In the southern rainforest, there is lower LAI in November. This is driven by lower surface DSR in November, which is a response to lower TOA DSR and higher cloud cover. The difference in VPD between March and November is very small and not sufficient to cause lower transpiration. The lower LAI alone explains lower transpiration, and therefore lower evaporation, in November than March. LAI and transpiration are much lower in November than March at 2°S, 28°E, and this reflects the influence of mesoscale convective systems that develop in the afternoon in November but not in March (Jackson et al. 2009, Hart et al. 2019). These storms block DSR and strongly suppress LAI, transpiration, and evaporation.
3. In the north-eastern savannah, there is lower LAI in November. This is driven by lower surface DSR in November, which is a response to higher cloud cover. The difference in VPD between March and November is not sufficient to cause lower transpiration. The lower LAI alone explains lower transpiration, and therefore lower evaporation, in November than March.
4. In the south-eastern savannah, there is lower LAI in November. This is driven by lower VWC, which occurs because a large soil moisture depletion between March and October outweighs a small soil moisture recovery between October and November. VPD is higher in November, and should cause higher transpiration, but this effect is overwhelmed by lower LAI, which explains lower transpiration, and therefore lower evaporation, in November than March.

Collectively, these contrasting controls on evaporation at the two rainfall peaks explain why the basin-wide average evaporation is lower in November than March.

Fig. 8 Flow chart showing the contrasting controls on evaporation at the two rainfall peaks in the four sub-domains around the basin. The results in each sub-domain are consistent with the Budyko framework for evaporation. The collective of these contrasting controls explains why there is lower evaporation in November than March on the basin-wide average

5.2 Consistency with the Budyko framework

We have confidence in our results that explain why evaporation is lower at the November rainfall peak than the March rainfall peak in each of the four sub-domains. This is because

the results are consistent with the Budyko framework, which defines how evaporation typically varies as a function of VWC and surface DSR (Budyko 1961). This framework contains three evaporation regimes: (1) dry regimes, where VWC is too low for evaporation to occur, (2) wet regimes,

where VWC is plentiful and evaporation varies in response to changes in surface DSR (energy availability), and (3) transition zones between wet and dry regimes, where evaporation varies in response to changes in VWC (water availability) (Fig. 5 from Seneviratne et al. 2010).

The Budyko framework states that if evaporation is lower in one month than another when both months have a wet regime, then lower surface DSR must be the reason why evaporation is lower. Our findings agree with this for the northern rainforest, the southern rainforest and the north-eastern savannah, as VWC is plentiful in both March and November, and lower surface DSR is the main reason why LAI, transpiration and therefore evaporation are lower in November than March. The Budyko framework also states that if evaporation is lower in one month than another, when the first month has a wet regime and the second has a transition regime, then lower VWC must be the reason why evaporation is lower. Our findings agree with this for the south-eastern savannah, as VWC is plentiful in March but moderate in November, and lower VWC is the main reason why LAI, transpiration and therefore evaporation are lower in November than March.

6 Conclusions

In this study, we have developed an understanding of why Congo Basin evaporation is lower at the November rainfall peak than the March rainfall peak on the basin-wide average, despite similar amounts of rainfall in an equatorial climate. The key findings are as follows:

1. LandFlux-EVAL data show that evaporation is lower in November than March in the rainforest and the eastern savannah (Fig. 3a).
2. The ERA5-Land reanalysis, which effectively reproduces the pattern of lower evaporation in November than March in LandFlux-EVAL, shows that transpiration is the main component of evaporation responsible for lower evaporation in November than March in the rainforest and the eastern savannah (Fig. 4c).
3. Using ERA5-Land, we find the following contrasting controls on transpiration, and therefore evaporation, at the two rainfall peaks in the rainforest and the eastern savannah:
 - (a) In the northern rainforest, there is lower LAI in November, driven by lower surface DSR. Additionally, there is lower VPD in November, driven by lower sensible heat flux from the leaves at the top of the canopy, that results from lower surface net radiation. The combination of lower LAI and VPD explains lower transpiration, and therefore lower evaporation, in November compared to March (Sect. 4).
 - (b) In the southern rainforest, and in the north-eastern savannah, there is lower LAI in November, driven by lower surface DSR. This lower LAI alone explains lower transpiration, and therefore lower evaporation, in November compared to March (Sect. 4).
 - (c) In the south-eastern savannah, there is lower LAI in November, driven by lower VWC. This lower LAI alone explains lower transpiration, and therefore lower evaporation, in November compared to March (Sect. 4).
4. Collectively, these contrasting controls on evaporation at the two rainfall peaks in the four sub-domains around the basin explain why there is lower transpiration, and therefore lower evaporation, at the November rainfall peak than the March rainfall peak on the basin-wide average. We have confidence in our results for the four sub-domains, because these results are consistent with the Budyko framework for evaporation.

Only by considering lower evaporation in November than March on the basin-wide average as the collective of contrasting controls on evaporation in specific basin regions were we able to move towards a physical understanding of the mechanisms that control the imbalance in evaporation between the two rainfall peaks. Therefore, to understand what controls the full seasonal cycle of evaporation on the basin-wide average, a regional approach is also needed. A follow up study, in preparation by the authors, begins this regional research.

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Appendix

Appendix 1: LAI

Total LAI is derived from ERA5-Land as the sum of LAI from low vegetation and LAI from high vegetation. Monthly LAI values are prescribed in ERA5-Land using data from the MODIS Collection 5 satellite product (Boussetta et al. 2013).

Appendix 2: VPD

We use near-surface air temperature and near-surface dew point temperature from ERA5-Land to calculate VPD. The Tetens approximation is used to calculate SVP as follows:

$$e_s(T) = 6.112 \exp\left(\frac{17.67T}{T + 237.3}\right) \quad (1)$$

where $e_s(T)$ is the SVP (hPa), and T is the near-surface air temperature (°C).

The Magnus approximation is then used to calculate relative humidity as follows:

$$RH = 100 \exp\left(\frac{17.625 \times 243.04 \times (T_d - T)}{(243.04 + T_d)(243.04 + T)}\right) \quad (2)$$

where RH is the relative humidity (%) and T_d is the near-surface dew point temperature (°C).

AVP is then calculated as follows:

$$e = \frac{RH}{100} e_s(T) \quad (3)$$

where e is the AVP (hPa). Finally, VPD is calculated as follows:

$$VPD = \frac{e_s(T)}{10} - \frac{e}{10} \quad (4)$$

where kPa is the unit.

Appendix 3: VWC

VWC is available for 0–7 cm, 7–28 cm, and 28–100 cm layers in ERA5-Land. We therefore calculate 1 m VWC as the weighted mean of the VWC from these three layers.

Appendix 4: Surface DSR

Surface DSR is equal to (1) TOA DSR + (2) the reduction in surface DSR due to cloud cover ('cloud forcing') + (3) the reduction in surface DSR due to atmospheric absorption ('atmospheric forcing'). (1) is available directly from

ERA5-Land. (2) is calculated as surface DSR with cloud ('average sky') minus surface DSR without cloud ('clear sky'). As surface DSR = (1) + (2) + (3), (3) is calculated as surface DSR – (1) – (2).

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