Dry Periods Amplify the Amazon and Congo Forests' Rainfall Self-Reliance

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Abstract

A substantial amount of the tropical forests of South America and Africa is generated through moisture recycling (i.e., forest rainfall self-reliance). Thus, deforestation that reduces evaporation and dampens the water cycle can further increase the risk of water-stress-induced forest loss in downwind areas, particularly during water scarce periods. However, few studies have investigated dry period forest rainfall self-reliance over longer records and consistently compared the rainforest moisture recycling in both continents. Here, we analyze dry-season anomalies of moisture recycling for mean-years and dry-years, in the South American (Amazon) and African (Congo) rainforests over the years 1980-2013. We find that, in the dry seasons, the reliance of forest rainfall on their own moisture supply (ρfor) increases by 7% (from a mean annual value of 26% to 28%) in the Amazon and up to 30% (from 28% to 36%) in the Congo. Dry years further amplify dry season ρfor in both regions by 4-5%. In both the Amazon and Congo, dry season amplification of ρfor is strongest in regions with a high mean annual ρfor. In the Amazon, forest rainfall self-reliance has declined over time. At the country scale, dry season ρfor can differ drastically from mean annual ρfor. In for example Bolivia and Gabon, mean annual ρfor is ˜30% while dry season ρfor is ˜50%. The dry period amplification of forest rainfall self-reliance further highlights the role of forests for sustaining their own resilience, and for maintaining downwind rainfall at both regional and national scales.

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Key Points:

- In South America, and particularly Africa, the share of forest rainfall that originates from the forest itself is higher in dry seasons.
- Dry years further amplify rainfall self-reliance.
- Several countries in Africa receive up to half of their rainfall from rainforests during dry seasons and dry years.

Abstract

A substantial amount of the tropical forests of South America and Africa is generated through moisture recycling (i.e., forest rainfall self-reliance). Thus, deforestation that reduces evaporation and dampens the water cycle can further increase the risk of water-stress-induced forest loss in downwind areas, particularly during water scarce periods. However, few studies have investigated dry period forest rainfall self-reliance over longer records and consistently compared the rainforest moisture recycling in both continents. Here, we analyze dry-season anomalies of moisture recycling for mean-years and dry-years, in the South American (Amazon) and African (Congo) rainforests over the years 1980-2013. We find that, in the dry seasons, the reliance of forest rainfall on their own moisture supply (ρ_{for}) increases by 7% (from a mean annual value of 26% to 28%) in the Amazon and up to 30% (from 28% to 36%) in the Congo. Dry years further amplify dry season ρ_{for} in both regions by 4-5%. In both the Amazon and Congo, dry season amplification of ρ_{for} is strongest in regions with a high mean annual ρ_{for}. In the Amazon, forest rainfall self-reliance has declined over time. At the country scale, dry season ρ_{for} can differ drastically from mean annual ρ_{for}. In for example Bolivia and Gabon, mean annual ρ_{for} is ~30% while dry season ρ_{for} is ~50%. The dry period amplification of forest rainfall self-reliance further highlights the role of forests for sustaining their own resilience, and for maintaining downwind rainfall at both regional and national scales.

Plain Language Summary

A substantial amount of the rainfall over the South American and African tropical rainforest originate from moisture generated by the forests themselves. Therefore, forest loss can reduce rainfall and lead to water stress in downwind areas. Few studies have analyzed and compared how the two rainforests contribute to their own rainfall during dry periods. In this study, we analyzed three decades of data and found that a larger fraction of the rainfall over forests is generated by the forests themselves during dry periods than usual. Thus, rainforests are particularly important for the generation of its own rainfall, when rainfall levels are already low and when the rainforests are potentially most vulnerable to droughts. The degree of reliance of rainforest rainfall on its own moisture amplifies by 7% in the rainforests of South America, 30% in the African rainforests in dry seasons, and more during dry seasons in dry years. Locally, the amplification can be even stronger, particularly in areas where the rainfall self-reliance is already high under usual climate conditions. The dry period amplification of forest rainfall self-reliance underscores the importance of preserving forests in order to maintain water availability in the forests themselves and in downwind regions.

1 Introduction

The tropical rainforests of the Amazon and Congo are hotspots of global biodiversity (Pimm et al., 2014) and critical for the global carbon cycle (Hubau et al., 2020; Mitchard, 2018). However, deforestation is increasing (Silva Junior et al., 2021; Tchatchou, Sonwa, Anne, & Tiani, 2015) along with aridity and droughts over both regions (Dai, 2013; Duffy, Brando, Asner, & Field, 2015; Zhou et al., 2014). The drier hydroclimate negatively influences forest functioning (e.g., carbon sequestration and storage) and resilience, i.e., the forest ecosystem’s ability to absorb or withstand perturbations (Boulton, Lenton, & Boers, 2022; Forzieri, Dakos, Mcdowell, Ramdane, & Cescatti, 2022; Lewis, Edwards, & Galbraith, 2015; Malhi, Gardner, Goldsmith, Silman, & Zelazowski, 2014). Remote-sensing-based studies indicate that rainfall constitutes a key variable in determining the risk for forest-to-savanna transitions (Hirota, Holmgren, van Nes, & Scheffer, 2011; Staver, Archibald, & Levin, 2011).

Forest loss affects forest functioning and resilience directly, but also indirectly by reducing evaporation and subsequent rainfall through the perturbation of the water balance. Namely, the return of terrestrial evaporation as precipitation over land areas, termed *terrestrial moisture recycling*, allows evaporation change to cascade across the continents (Zemp et al., 2017). Atmospheric moisture tracking, based on e.g., water balance and data on atmospheric humidity, wind speed, evaporation, and precipitation, allows us to map and analyze the evaporative source of precipitation (i.e., moisture sources), and where evaporation falls out as precipitation (i.e., moisture sinks) (Keys et al., 2012; O. A. Tuinenburg & Staal, 2020; van der Ent, Savenije, Schaefli, & Steele-Dunne, 2010).

In parts of the Amazon and Congo rainforests, the percentage of precipitation from land can be up to 60-80%, i.e. the majority of the mean annual rainfall originates from terrestrial evaporation (Dominguez et al., 2022; Dyer et al., 2017; Spracklen, Arnold, & Taylor, 2012; Spracklen & Garcia-Carreras, 2015; van der Ent et al., 2010). This can be both a boon and a bane for forest resilience: retained vegetation transpiration helps to buffer against droughts by providing moisture for subsequent rainfall (Staal et al., 2018), while long-term moisture flow disruptions can lead to self-amplified forest loss (Wunderling et al., 2022; Zemp et al., 2017). Thus, where increased reliance of precipitation on forest moisture supply coincides with dry periods, it may enable both regional and global-scale self-reinforcing feedbacks between forest loss and drier conditions (Staal et al., 2020; Zemp et al., 2017). In the Amazon, stronger regional forest-rainfall relationships during dry periods have been suggested to increase the negative effects of deforestation for forest resilience (Bagley, Desai, Harding, Snyder, & Foley, 2014; Staal et al., 2018) and agriculture production (Leite-Filho, Soares-filho, Davis, Abrahão, & Börner, 2021). Further, due to a nonlinear relationship between atmospheric moisture content and rainfall, minor decrease in moisture content could reduce rainfall drastically (Baudena, Tuinenburg, Ferdinand, & Staal, 2021). However, studies have contrasting conclusions for temporal variations of the extent that rainforests depend on their own moisture supply for rainfall, which may be explained by differences in study region selection, methods, assumptions and time period considered (overview in Table S2 and S3).

In the Amazon, some atmospheric moisture studies suggest that forest rainfall self-reliance is highest in the dry season (Angelini et al., 2011; Burde, Gandush, & Bayarjargal, 2006; Eltahir & Bras, 1994; Staal et al., 2018; Zemp et al., 2014), while others suggest the wet season (Burde et al., 2006; Satyamurty, da Costa, & Manzi, 2013). Consistent with a higher rainfall self-reliance during the dry season, Spracklen et al., (2012) showed that deforestation leads to a larger rainfall reduction in the dry season (-21% change) than in the wet season (-12% change). Dry season rainfall self-reliance (in percent) has been shown to be about 7% higher during the two mega-drought years 2005 and 2010 relative to wet years (Bagley et al., 2014). Such dry-year dry-season anomaly are important to understand as any marginal increase in water deficit during the dry season can have a large impact, e.g., on streamflow and carbon balance (Marengo, Tomasella, Alves, Soares, & Rodriguez, 2011; Mitchard, 2018).

Estimates of rainfall self-reliance also vary in the Congo. Pokam, Djiotang, & Mkankam (2012) report the highest ratios during both dry seasons December-January-February and June-July-August for a rectangular region mostly over the forested regions. Dyer et al., (2017), who selected a rectangular region over the basin, observed the highest ratio during the June-July-August dry season, but below-average ratios during the other dry season December-January-February. In contrast, Sorí, Nieto, Vicente-Serrano, Drumond, & Gimeno (2017), who used the actual basin delineation, suggest that basin rainfall self-reliance are the highest in the rainy season, and below average in the dry season month July. (Sorí et al., 2017)(Sorí et al., 2017)(Sorí et al., 2017)(Sorí et al., 2017)(Sorí et al., 2017)While discrepancies remain regarding the spatio-temporal variability of continental moisture recycling in the Congo, higher rainfall dependency on terrestrial evaporation sources in dry seasons is also indicated by isotope studies (Worden, Fu, Chakraborty, Liu, & Worden, 2021).

Previous studies suggest that increased forest rainfall self-reliance during dry periods may be associated with reduced oceanic moisture inflow, and increased forest transpiration due to higher incoming radiation and forests' ability to store and access subsoil water (Bagley et al., 2014; Costa et al., 2010; O'Connor et al., 2021; Staal et al., 2018; Zemp et al., 2014). High evaporation from the Amazon has also been associated with the presence of lower-level jets during the dry season (Nascimento, Herdies, & De Souza, 2016). Sorí et al. (2017) explains that the weakening of the Congo basin rainfall self-reliance in dry years is due to vertically integrated moisture flux divergence that favor moisture export from the basin. However, questions remain with regard to the respective attribution of moisture recycling anomalies to either anomalies in wind patterns or evaporation, which for example can be relevant for understanding deforestation impacts on forest rainfall.

Because moisture recycling over the Amazon and Congo is often examined in different studies with different methodologies, cross-comparisons between the two major rainforest systems often cannot be easily made. Despite the importance of rainfall for forest functioning and resilience (e.g. Singh, van der Ent, Wang-Erlandsson, & Fetzer, (2022)), we still have limited knowledge of how variations in forest self-reliance may potentially interact with dry periods and deforestation to negatively impact forest rainfall, and how this process might differ between the Amazon and Congo.

This study aims to investigate the importance of the moisture supply from rainforests in South America and Africa for their own rainfall during dry periods, i.e., average dry seasons and dry seasons in dry years. Based on atmospheric moisture tracking of forest moisture sources and sinks over 34 years, we address the following questions: *i.* What are the dry period anomalies of forest moisture sources and sinks? (Sect. 4.1, 4.2); *ii.* Are dry period anomalies larger in regions with high mean annual forest rainfall self-reliance? (Sect. 4.3); *iii.* To what extent do dry period anomalies of forest evaporation contribute to dry period anomalies of forest rainfall self-reliance? (Sect. 4.4), and *iv.* How do dry periods affect countries' rainfall reliance on forest moisture? (Sect. 4.5).

2. Materials and methods

2.1 Moisture recycling model

The Eulerian moisture tracking model WAM-2layers (van der Ent, Wang-Erlandsson, Keys, & Savenije, 2014) was used to track moisture sources of precipitation and destination of evaporation for the Amazon and Congo forest. WAM-2layers tracks atmospheric moisture from zero pressure to surface pressure (i.e., from zero pressure at the top of atmosphere to the atmospheric pressure at a location on Earth's surface) in two layers. The model applies the water balance, and assumes the atmosphere is well mixed within each of the two atmospheric layers. To track where evaporation from a given region (source region) falls as precipitation (sink region), moisture is tracked forward as follows:

$$\frac{\partial S_{\text{tracked}}}{\partial t} = -\frac{\partial\left(S_{\text{tracked}}u\right)}{\partial x} - \frac{\partial\left(S_{\text{tracked}}v\right)}{\partial y} + E_{\text{tracked}} - P_{\text{tracked}} \pm F_{\text{vertical,tracked}} \quad (1)$$

where S_{tracked} is the tracked atmospheric storage in an atmospheric column in one layer, t is time, u and v are wind components in the x zonal and y meridional directions, E_{tracked} is tracked evaporation entering and P_{tracked} is precipitation leaving an atmospheric column in one layer, and $F_{\text{vertical,tracked}}$ is the tracked vertical moisture transport between the two atmospheric layers. Evaporation in this paper refers to the total of all types of upward going vapor flows (i.e., ocean evaporation, transpiration, interception evaporation, soil evaporation, and open water evaporation) (Miralles, Brutsaert, Dolman, & Gash, 2020), and the terrestrial and forest evaporation flows that we track naturally preclude the ocean evaporation component. Backward tracking to determine the source of precipitation uses an analogous equation. We used WAM-2layers to track moisture for the years 1979-2014, of which 1979 and 2014 were used as spin-up for the forward and backward tracking, respectively.

WAM-2layers has been extensively used to characterize the fate and properties of the atmospheric branch of the water cycle (e.g., Benedict, van Heerwaarden, van der Linden, Weerts, & Hazeleger, (2021); Keys et al., (2014); Link, van der Ent, Berger, Eisner, & Finkbeiner, (2020); van der Ent & Tuinenburg, (2017); Xiao & Cui, (2021)). The moisture tracking performance generally compares well with Lagrangian type multi-atmospheric-layers moisture tracking and regional climate model online tracking (van der Ent, Tuinenburg, Knoche, Kunstmann, & Savenije, 2013), We used a MATLAB version of the model, which is, however, equivalent in terms of process descriptions as the model used in (van der Ent et al., 2014).

2.2 Data analyses

2.2.1 Study regions and time periods

Moisture tracking was applied to 1.5°x1.5° grid cells in South America and Africa with at least 85% tropical evergreen broadleaf forest cover (hereafter referred to as Amazon and Congo forests). Averaged over the entire study region, each of the two forests has a forest cover of more than 97%. Monthly variations of moisture recycling metrics are shown (in Sect. 4.3) for forest moisture source and sink hotspots, here defined as the 25% of the forest grid cells with the highest ratios of precipitation from forests and evaporation to forests, respectively.

We consider two types of anomalies in this study: (1) the anomaly of dry season in mean years compared to mean annual ('dry season anomaly'), and (2) the anomaly of the dry season in dry years compared to the dry season in mean years ('dry-year dry-season anomaly'). Based on the mean precipitation patterns in the study regions, we select June to September as the dry season months for South America, and January-February and June-July-August for Africa, see Table S1.

We chose to include the six driest years in our analyses, where dryness is defined by the intensity of maximum climatological water deficit (MCWD) (years denoted as Y_{MCWD}). The MCWD captures the drought years well: the three driest years selected here for the Amazon (2010, 2005, 1998) based on MCWD also correspond to the three known drought years with large effects on forest mortality (Lewis, Brando, Phillips, Heijden, & Nepstad, 2010; Williamson et al., 2000), which are associated with warming anomalies of the tropical North Atlantic (Marengo et al., 2011).

MCWD is defined as the most negative value of climatological water deficit C_m [mm], which is estimated based on monthly precipitation and a fixed reference evaporation rate E_{fix} at 3.3 mm day^{-1} (used instead of actual E in order to represent the climatological drought) (Malhi et al., 2009; Zemp et al., 2017):

$$C_m = \min\left(0, C_{m-1} + \int_{d_{m,0}}^{d_{m,end}} P_{Y,m} - \int_{d_{m,0}}^{d_{m,end}} E_{\mathrm{fix}}\right) \quad (2)$$

where m denotes the month number, $d_{\mathrm{m,0}}$ and $d_{\mathrm{m,end}}$ the first and last day of a month, $P_{\mathrm{Y,m}}$ is the precipitation for year Y and month m, and C_0 is 0. The climatological water deficit C is accumulated continuously and reset to zero at the wettest month of the year, at which the next 12-month period calculation cycle starts (Malhi et al., 2009).

2.2.2 Moisture recycling analyses and terminology

The fraction of rainfall reliance on forest moisture sources ρ_{for} [-] (i.e., forest precipitation recycling ratio) is defined as:

$$\rho_{\text{for}} = P_{\text{for}} / P \quad , \tag{3}$$

where P_{for} [L^3 time^{-1} or L time^{-1}] refers to precipitation with forest origin. The ρ_{for} are estimated for all grid cells globally, and only the ρ_{for} values within the forested regions indicate the forest's rainfall self-reliance (i.e., the rainforest rainfall reliance on forest moisture sources).

The fraction of rainfall reliance on terrestrial moisture sources ρ_{terr} [-] (i.e., terrestrial precipitation recycling ratio) is similarly defined as

$$\rho_{\text{terr}} = P_{\text{terr}} / P \quad , \tag{4}$$

where P_{terr} [L^3 time^{-1} or L time^{-1}] denotes precipitation with terrestrial origin at the global scale.

The fraction of evaporation that contribute to forest rainfall ε_{for} [-] (i.e., forest evaporation recycling ratio) is defined as:

$$\varepsilon_{\text{for}} = E_{\text{for}} / E \quad , \tag{5}$$

where E_{for} [L^3 time^{-1} or L time^{-1}] refers to evaporation that falls as rainfall in areas with forest cover > 85%.

Linear trends are calculated by least squares using the Climate Data Toolbox for MATLAB (Greene et al., 2019).

We analyzed both absolute and relative dry period differences from mean annual or seasonal recycling values. The *absolute* dry period recycling anomalies are the difference between dry period and mean years recycling values, e.g., the absolute dry season anomaly of terrestrial precipitation recycling ratio is:

$$\Delta\rho_{\text{terr,dry-season, abs}} = \rho_{\text{terr,dry-season}} - \rho_{\text{terr,mean-annual}} \quad (6).$$

The *relative* dry season recycling anomalies are calculated in relation to the mean annual recycling values, e.g., the relative dry season anomaly of terrestrial precipitation recycling ratio is:

$$\Delta\rho_{\text{terr,dry-season, rel}} = \left(\rho_{\text{terr,dry-season}} - \rho_{\text{terr,mean-annual}}\right)/\rho_{\text{terr,mean-annual}} \quad (7).$$

Finally, the *relative* dry-year dry-season recycling anomalies are calculated in relation to the dry season recycling values, e.g., the relative dry-year dry-season anomaly of terrestrial precipitation recycling ratio is:

$$\Delta\rho_{\text{terr,dry-year-dry-season, rel}} = \left(\rho_{\text{terr,dry-year}} - \rho_{\text{terr,dry-season}}\right)/\rho_{\text{terr,dry-season}} \quad (8).$$

2.2.3 Correspondence and contrariety between anomalies of the total evaporation and the evaporation that becomes forest rainfall

Anomalies of E_{for} can be caused by anomalies in E in source regions and/or by anomalies in other meteorological conditions (such as regional wind patterns and rainfall generation in sink region). As a means to analyze their respective role of E contribution to E_{for} anomalies, we compare the mean absolute volumetric E_{for} anomalies with E anomalies. E_{for} anomalies that correspond well with E anomalies can be interpreted as mainly E driven, whereas contrariety shows regions where E instead buffers against meteorologically driven E_{for} anomalies.

Each positive and negative E_{for} anomaly is comprised of four parts (see example in Figure 1):

- *total correspondence,* where an E anomaly agrees in sign with, and is larger than or equal to, the E_{for} anomaly;

- *partial correspondence*, where an E anomaly agrees in sign with, but is smaller than, the E_{for} anomaly;
- *partial contrariety*, where an E anomaly disagrees in sign with, and is smaller than, the E_{for} anomaly; and
- *total contrariety*, where an E anomaly disagrees in sign with, and is larger than or equal to, the E_{for} anomaly.

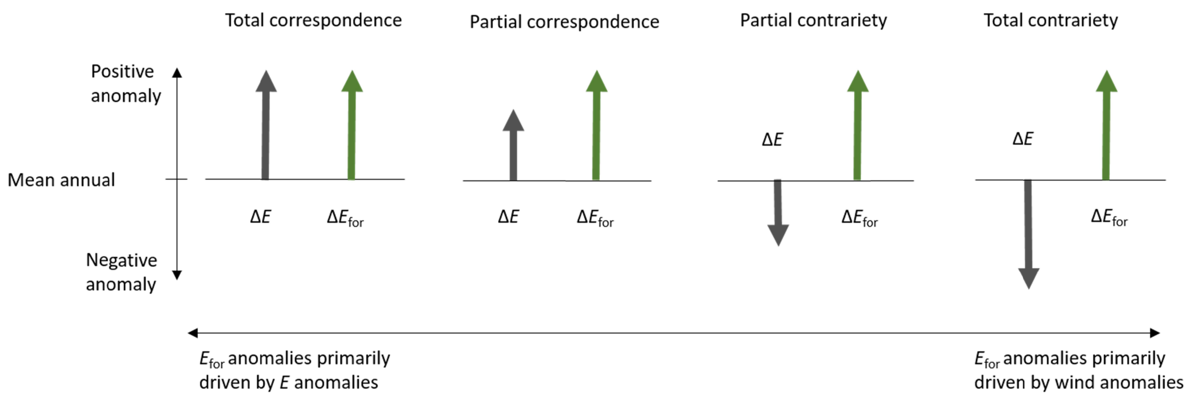

Figure 1. Illustration of four categories of the correspondence and contrariety between anomalies of evaporation (ΔE) and evaporation destined for forest rainfall (ΔE_{for}). The conceptual figure illustrates the case where ΔE_{for} is positive.

To elicit the role of forest and terrestrial E specifically, each of the four categories is summarized for forested land and all land (results shown in Sect. 4.2).

3 Data

For our investigations on moisture recycling, we used the following meteorological data from the ERA-Interim (ERA-I) reanalysis at 1.5° resolution provided by the European Centre for Medium Range Weather Forecast (ECMWF) (Dee et al., 2011): specific humidity and zonal and meridional wind speed at 17 model levels from zero pressure to surface pressure at 6 hours resolution, and evaporation and ocean precipitation data at 3 hour resolution. Comparison between ERA-I and MERRA data shows that ERA-I offers good moisture recycling performance over both South America and Africa (Keys et al., 2014). ERA-I precipitation over Congo is, however, overestimated as suggested by water balance comparison (Figure S1) with Global Runoff Data Centre (GRDC) runoff data (Fekete, Vörösmarty, & Grabs, 2002) and shown in other studies (e.g., Lorenz & Kunstmann, 2011).

Thus, the land precipitation used in the moisture recycling analyses were instead taken from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) v1.1 (Beck et al., 2016) at 3-hour temporal resolution. The data was originally in 0.25º spatial resolution, and up-scaled to 1.5º by simple aggregation. This precipitation product results from optimally combined information from two gauge observation based datasets (CPC Unified and GPCC), three satellite based datasets (CMORPH, GSMaP-MVK, and TMPA 3B42RT), and two reanalysis (ERA-Interim and JRA-55) datasets. Water balance comparison of effective precipitation (i.e., mean annual precipitation minus evaporation) with GRDC runoff shown in Fig. S1 indicates that the precipitation and evaporation products used in this study (Fig. S2a,b) are in agreement with the runoff data for the Amazon and Congo regions. Mean-years and dry-years dry season anomalies of precipitation and evaporation are shown in Fig. S3 and S4. All meteorological data downloaded cover a 36 years period 1979–2014.

Land cover data for delineating the Amazon and Congo study regions were taken from the Land Cover Type Climate Modeling Grid (CMG) MCD12C1 International Geosphere Biosphere Program (IGBP) land classification created from Terra Moderate Resolution Imaging Spectroradiometer (MODIS) data (Friedl et al., 2010) for the year 2005.

4 Results

4.1 Moisture recycling characteristics

The mean annual fraction of forest rainfall that originates from forest moisture sources (ρ_{for}) is similar between the Amazon (26%) and the Congo (28%) (Table 1), although reliance on terrestrial moisture sources (ρ_{terr}) is higher in the Congo (64%) than in the Amazon (42%). Notably, the fraction of forest evaporation that also falls as forest rainfall (ε_{for}) is higher in the Amazon (38%) than in the Congo (26%).

In dry seasons, rainfall reliance on forest and terrestrial moisture sources (i.e., ρ_{for} and ρ_{terr}) in both regions increase, while the fraction of evaporation that becomes forest rainfall (i.e., ε_{for}) decreases. On average, the dry season reliance on forest moisture sources (ρ_{for}) is higher than the mean annual values by almost 7% in the Amazon (JJAS), 2% in the Congo JF-season and ~30% in the Congo JJA-season. Dry season reliance on terrestrial sources (ρ_{for}) is also higher than the mean annual reliance for both forests: by 13% in the Amazon (JJAS), 8% in Congo JF-season, and 11% in the Congo JJA-season.

In dry years, the dry season reliance on forest moisture further increases by ~4-5% in the Amazon and Congo, whereas further increase in the reliance on terrestrial sources is slightly more modest (3% in the Amazon, 1% in the Congo JF-season, and 4% in the Congo JJA-season). In contrast, a smaller fraction of the dry season forest evaporation becomes forest rainfall (ε_{for}) in dry years, both in the Amazon (-16%) and in the Congo (-19% in the JF season, and -9% in the JJA season). Thus, the forest and terrestrial precipitation recycling ratios are highest, whereas evaporation recycling ratios are lowest during the dry seasons in dry years across all study regions.

Table 1. Overview of moisture recycling metrics in the Amazon and Congo forests. The first three columns show the percentage of forest rainfall from forest, the percentage of forest rainfall from land, and the percentage of forest evaporation to forests (i.e., mean ρ_{for}, ρ_{terr} and ε_{for} *of the Amazon and Congo rainforests). The last two columns show the relative dry season and dry-year dry-season anomalies (see definitions in Sect. 2.2.2). The highest value for each recycling ratio metric is in* ***bold****.*

Region (dry season months)	Mean recycling ratios (ρ or ε, %), see Eq. 3			Mean dry period anomalies				Standard deviation (p.p.)	
	Annual	Dry season	Dry season in dry years	Dry season difference from mean annual, see Eq. 7		Dry-year dry-season difference from mean dry season, see Eq. 8		Seasonal	Dry season inter-annual
				%	p.p.	%	p.p.		
$\boldsymbol{\rho}_{\mathbf{terr}}$									
Amazon (JJAS)	42.3	47.6	**48.9**	12.7	5.4	2.7	1.3	±5.5	±1.6
Congo (JF)	63.8	68.5	**69.0**	7.5	4.7	0.71	0.5	±6.3	±4.4
Congo (JJA)	63.8	70.6	**73.2**	10.6	6.8	3.8	2.6	±5.8	±3.3
$\boldsymbol{\rho}_{\mathbf{for}}$									
Amazon (JJAS)	26.1	27.9	**29.0.**	6.6	1.7	4.0	1.1	±3.7	±1.9
Congo (JF)	27.8	28.4	**29.8**	2.0	0.5	5.0	1.4	±6.4	±3.6
Congo (JJA)	27.8	36.2	**37.8**	30.1	8.4	4.5	2.6	±5.5	±3.4
$\boldsymbol{\varepsilon}_{\mathbf{for}}$									
Amazon (JJAS)	**38.4**	25.0	21.1	-34.9	-13.4	-15.7	-3.9	±10.3	±3.3
Congo (JF)	**26.4**	19.2	15.5	-27.2	-7.2	-19.4	-3.7	±7.2	±3.5
Congo (JJA)	**26.4**	25.2	23.0	-4.5	-1.2	-9.0	-2.3	±6.7	±3.3

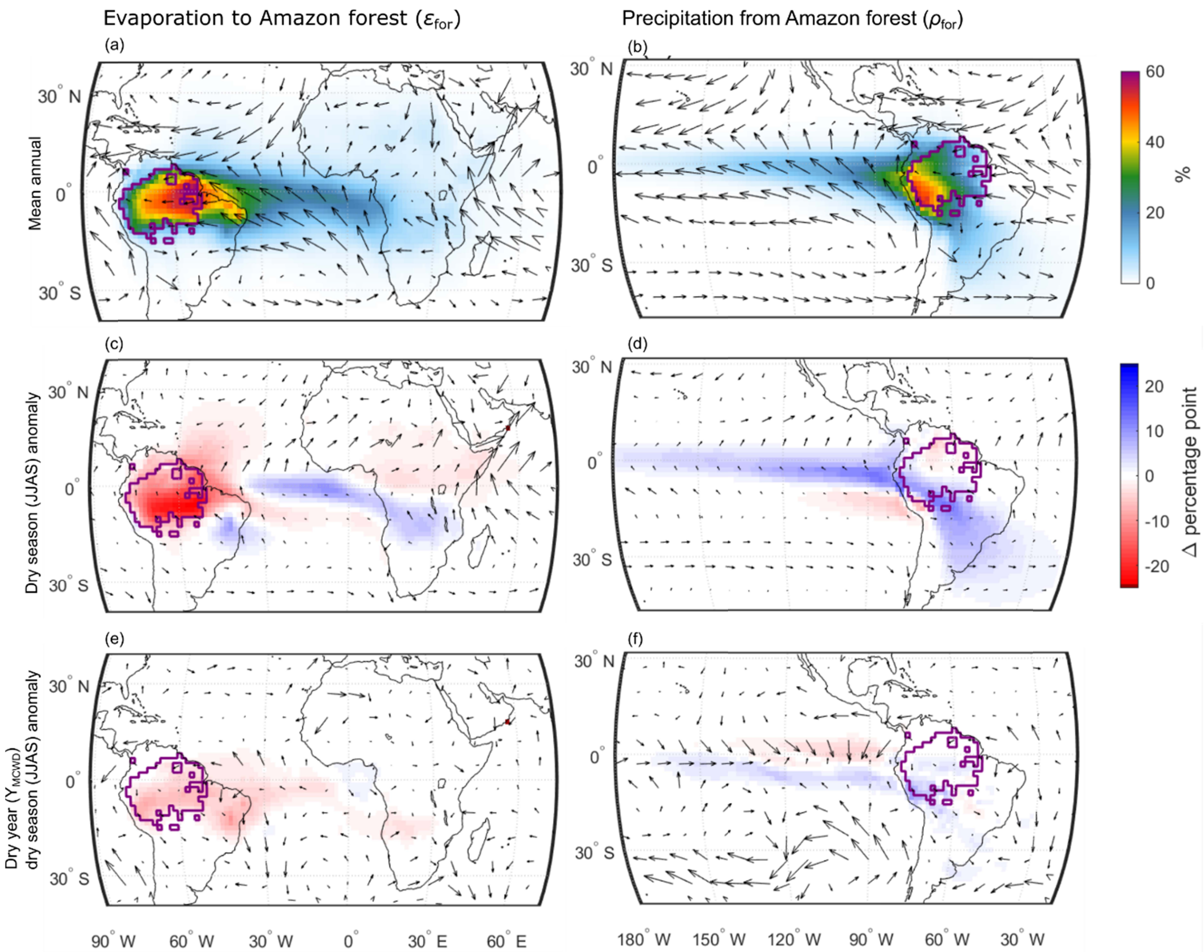

Figure 2. The percentage of evaporation destined for the Amazon forest (ε_{for}) and percentage of precipitation originating from the Amazon forest (ρ_{for}) at the ***(a, b)*** *mean annual values, and their anomalies in the* ***(c, d)*** *dry season (in percentage point difference between the dry season and the mean annual), and* ***(e,f)*** *dry year (in percentage point difference between the dry season in dry years and the mean dry season over all years). The arrows represent wind directions in the lower atmosphere, and the purple lines denote the forest boundaries. For study region and time period selections, see Sect. 2.1.1 and Table S1, and for moisture recycling metrics definitions, see Sect. 2.2.2.*

In the Amazon, the mean annual rainfall reliance on both forest and terrestrial moisture sources is the highest in the southwest (up to ~50% for ρ_{for}, see Figure 2b; and ~60% for ρ_{terr}, see

Fig. S2c). In contrast, the areas where the highest fraction of evaporation recycled within the forest region are in the east (up to ~60%, Figure 2a). The moisture source for forest moisture recycling is, thus, concentrated in eastern Amazon, and the moisture sink concentrated in southwestern Amazon. These patterns follow from wind patterns and are distinctly influenced by topography. The Andes to the west effectively block east-to-west moisture transport, leading to particularly high ρ_{terr} and ρ_{for} along the mountain range. In absolute numbers, similar moisture recycling patterns are found for E_{for} and P_{for}, although high values of P_{for} are also found in the northwest where ρ_{for} appears to be moderate (compare Figure 2b and Figure S5b).

In the Amazon dry season, the relative rainfall reliance on forest moisture (ρ_{for}) is higher than the mean annual in the southwestern parts (Figure 2d), despite an overall higher absolute amount of precipitation with forest origin (P_{for}) (Figure S5b). Furthermore, the fraction of dry season evaporation that falls as rainfall over forests (ε_{for}) is below the mean annual in almost the entire forest region (Figure 2c). Instead, there is a higher than mean evaporative contribution from the equatorial Atlantic Ocean, as well as parts of central Africa and southeastern Brazil (Figure 2c). In the Amazon dry years (defined in Table S1), the dry season ε_{for} decreases further across the entire forest region except in the northwest (Figure 2e), whereas the dry season ρ_{for} further increases in the southwest (Figure 2f). However, in absolute moisture volumes, both the dry season P sources and E sinks are lower in dry years (Figure S5e,f).

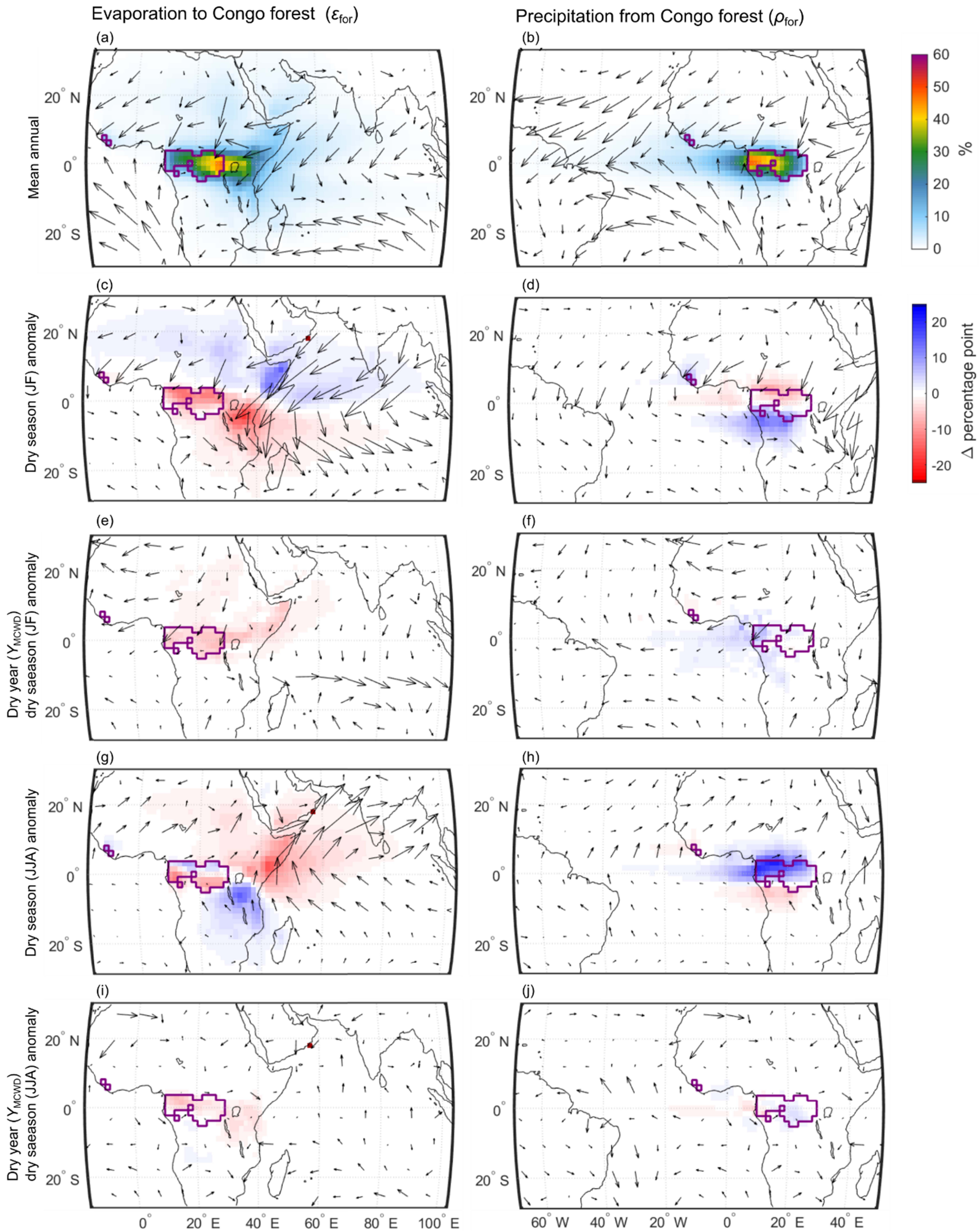

Figure 3. The percentage of evaporation that goes to Congo forest and the percentage of precipitation originating from the Congo forest at the ***(a, b)*** *mean annual scale, and their absolute anomalies in the* ***(c, d)*** *January-February (JF) dry season (i.e., difference between the*

JF and the mean annual), ***(e,f)*** *dry year (i.e., between the JF in dry years and the mean JF over all years),* ***(g, h)*** *June-July-August (JJA) dry season (i.e., difference between the JJA and the mean annual), and* ***(i,j)*** *dry year (i.e., between the JJA in dry years and the mean JJA over all years). The arrows represent wind directions in the lower atmosphere, and the purple lines denote the forest boundaries considered as sink and source regions respectively. For study region and time period selections, see Sect.2.2.1, and for moisture recycling metrics definitions, see Sect. 2.2.2.*

In the Congo, the mean annual rainfall reliance on both forest and terrestrial moisture sources is the highest in the west (up to ~50% for ρ_{for}, see Figure 3b; and up to ~80% for ρ_{terr}, see Figure S2c). In contrast, the areas where the highest fraction of evaporation recycled within the forest region are in the east (up to ~45%, Figure 3a) and the Great Lakes region east of Congo forest (up to ~40%, Figure 3a). Thus, similarly to the Amazon, the moisture source for forest moisture recycling is concentrated in the east, and the moisture sink in the west following predominating wind patterns. In absolute numbers, similar moisture recycling patterns are found for E_{for} and P_{for} (Figure S6ab), although high values of P_{for} are also found in the central parts where ρ_{for} appears to be moderate (compare Figure 3b and Figure S6b).

In the Congo JF season, moisture supply to the Congo forest is higher than the mean annual in the Horn of Africa and the Indian Ocean ($\varepsilon_{\mathrm{for}}$ in Figure 3c, and E_{for} in Figure S6c). Note, however, that while the fraction of evaporation in the Horn of Africa that contributes to forest precipitation ($\varepsilon_{\mathrm{for}}$) is higher during the JF season (Figure 3c), the absolute amounts are small (Figure S6c). In the northern Congo forest, all forest recycling metrics ($\varepsilon_{\mathrm{for}}$, E_{for}, ρ_{for}, P_{for}) are lower than mean annual during the JF season (Figure 3c, Figure S6c, Figure 3d, Figure S6d). Nevertheless, the rainfall reliance on forest moisture is higher both in southern parts of the forest and in areas south of the forest (ρ_{for} in Figure 3d, P_{for} in Figure S6d). Averaged over the forest region, the JF season ε_{for} is lower (JF: 19%; mean annual: 26%) and ρ_{for} is higher (JF: 69%; mean annual: 64%) than mean annual (Table 1). In dry years, the JF season moisture contribution to forests (ε_{for}, E_{for}) further decreases and rainfall reliance on forest moisture (ρ_{for}, P_{for}) further increases in the Congo forest region (Figure 3e,f, Figure S6e,f, Table 1).

In the Congo JJA season, the spatial patterns of moisture recycling anomalies are almost the opposite of the JF season anomalies, due to a reversal of the predominant wind directions associated with the seasonal shifts of the Inter-Tropical Convergence Zone (Figure 3c,d,g,h, and S6c,d,g,h). For instance, moisture supply to the Congo forest, which was higher than the mean annual in the JF season, is instead lower than the mean annual in the JJA season in the Horn of Africa and the Indian Ocean (ε_{for} in Figure 3g, and E_{for} in Figure S6g). Similarly, the precipitation recycling anomaly metrics are reversed between the JF and JJA seasons, and forest rainfall reliance on forest moisture is notably higher than average in the northern parts the forest in the JJA season (locally up to ~20 percentage points higher than mean annual, see Figure 3h and S6h)). In the dry years, slightly less evaporation in the western parts of the forest contributes to forest rainfall (Figure 3i, S6i), while slightly more forest rainfall in southern parts of Congo originates from the forest itself (Figure 3j, S6j).

4.2 Dry season amplification stronger in areas with high mean annual forest precipitation recycling

Across both the Amazon and Congo, the JJAS and JJA dry seasons tend to see higher anomalies of rainfall self-reliance in areas with high mean ρ_{for} (Figure 4ab). In Congo's dry JF season, however, dry season ρ_{for} anomalies tend to be lower in areas with lower mean annual ρ_{for} (see Figure 4c). Notably, the boreal summer dry season anomalies of ρ_{for} in the Amazon and Congo tend to be distinctly different from those of the wet seasons. The wet season ρ_{for} anomalies in the Amazon and the wet MA season anomalies in the Congo are not only negative, but also decrease with increasing mean annual ρ_{for} (Figure 4abc). In the Congo, ρ_{for} anomalies in the wet season (SON) are generally negative, but tend to be higher in areas with higher mean annual ρ_{for} (Figure 4b).

In the dry years, the differences between dry and wet seasons anomalies increase (Figure 4def). The dry-year dry-season anomalies tend to be positive, but lower in areas with high mean ρ_{for}. In contrast, the dry-year wet-seasons anomalies tend to be negative and increase with increasing mean annual ρ_{for}.

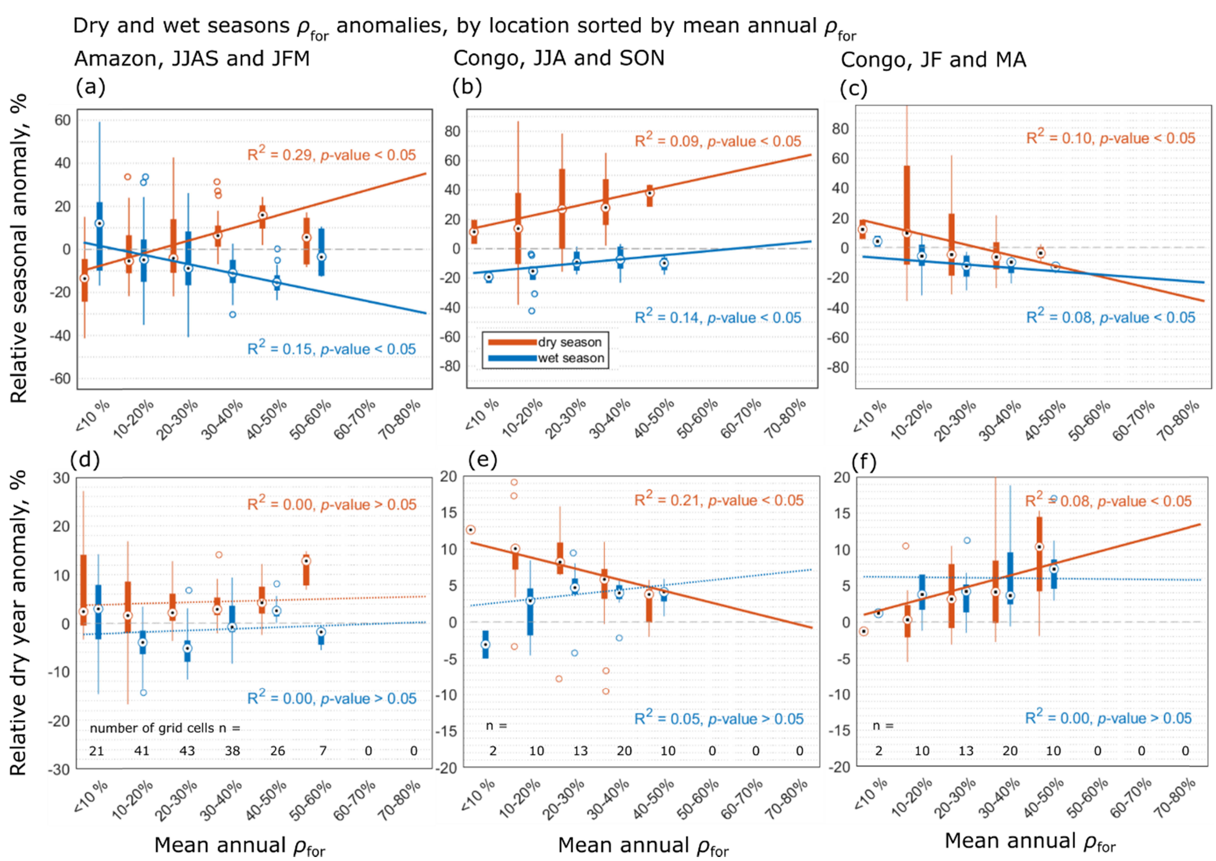

Figure 4. Relationships between seasonal anomalies of forest self-reliance (ρ_{for} in the Amazon and Congo forests, respectively) and mean annual ρ_{for} (a,d) the Amazon and (b,c,e,f) Congo. For

study region and time period selections, see Sect. 2.2.1, and for moisture recycling metrics definitions, see Sect. 2.2.2.

4.3 Climatology and trends in forest moisture source and sink regions

Monthly P and ρ_{terr} vary strongly with seasons (Figure 5a-d) in the Amazon and Congo forests, whereas forest $\varepsilon_{\mathrm{for}}$ and ρ_{for} tend to vary less, and forest E remain stable throughout the year. Overall, when P and $\varepsilon_{\mathrm{for}}$ are at their lowest in the dry seasons, whereas ρ_{terr} and ρ_{for} have the reversed seasonality and peak in dry seasons.

In the Amazon forest source hotspot (i.e., the 25% of the forest areas with the highest values of $\varepsilon_{\mathrm{for}}$), the median $\varepsilon_{\mathrm{for}}$ varies between 70% in March and 30% in July, while ρ_{for} remain below 20% throughout the year (Figure 5a). In the Amazon forest sink hotspot (i.e., the 25% of the forest areas with the highest values of ρ_{for}), the median $\varepsilon_{\mathrm{for}}$ varies between 40% in March/November and almost 10% in July, while ρ_{for} reaches 55% in the dry season and its value never drops below 35% (Figure 5b). Throughout the year, the Amazon sink ρ_{for} is about 10-15 percentage points lower than ρ_{terr} (ρ_{terr}: 50-70 %, and ρ_{for} : 35-55 %) (Figure 5b).

In the Congo source hotpot, the median $\varepsilon_{\mathrm{for}}$ varies between 50% in October and 30% in January, while ρ_{for} peaks at 25% in July (Figure 5c). In the Congo forest sink hotspot, ρ_{for} peaks most distinctly in the JJA season at 62% and never drops below 30%, whereas $\varepsilon_{\mathrm{for}}$ peaks at 45% in September and October and largely remains below 20-30%. In both the source and sink hotspots, ρ_{for} has one distinct peak in the JJA season, whereas ρ_{terr} peaks twice: once in the JF season and once in the JJA season. Because of this, the difference between ρ_{for} and ρ_{terr} is smallest in the JJA season (about 25-30 percentage point), when ρ_{terr} exceeds 85%.

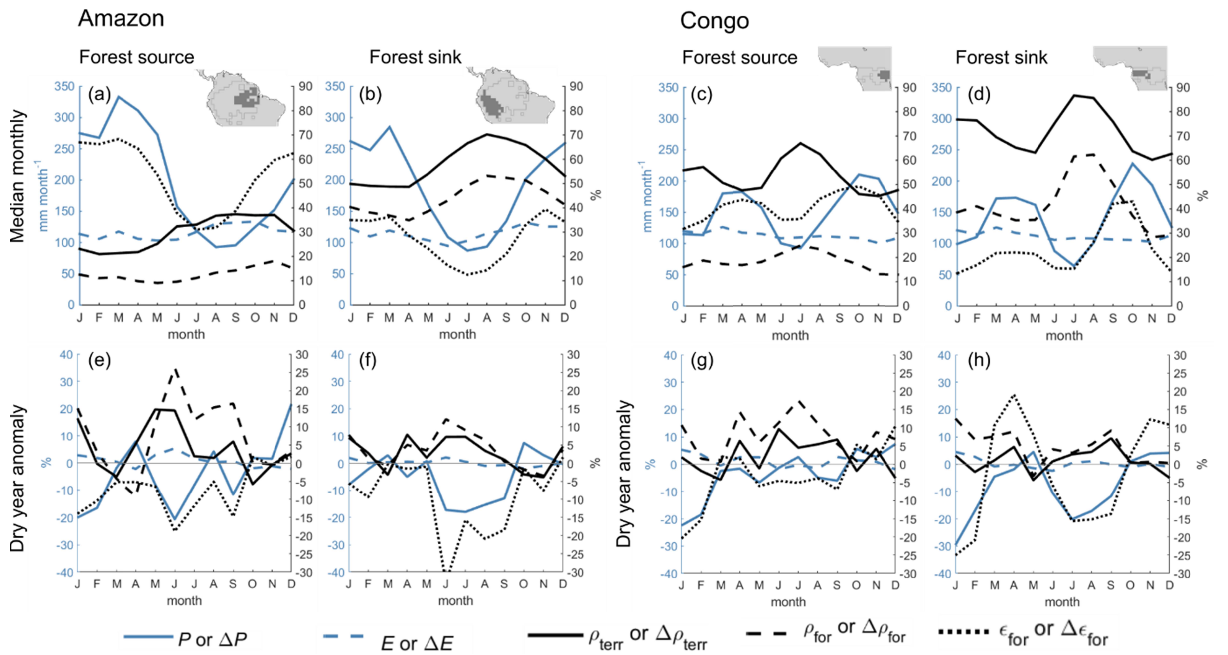

Figure 5. Monthly variations in precipitation (P, blue solid line), evaporation (E, blue dashed line), percentage of precipitation from land (ρ_{terr}, black solid line), percentage of precipitation from forest (ρ_{for}, black dashed line), percentage of evaporation to forest (ε_{for}, black dotted line), and their dry year anomalies over the study period 1980-2013 for the source and sink hotspots (dark grey in maps) in ***(a,b,e,f)*** *Amazon and* ***(c,d,g,h)*** *Congo. The anomalies* ***(e,f,g,h)*** *are given as the mean dry year values relative to median values of all years. For study region and time period selections, see Sect. 2.2.1, and for moisture recycling metrics definitions, see Sect. 2.2.2.*

The dry years anomalies (Figure 5e,f,g,h) do not have a consistent seasonal pattern. Only the Amazon forest has precipitation considerably lower than mean annual in the JJAS dry season, when also ρ_{for} and ρ_{terr} are higher than mean annual (up to 10% in the sink and up to 25% in the source hotspot) (Figure 5e,f). In the Congo forest, dry years increase only the relative role of moisture supply from forests: only ρ_{for} is increased in both hotspots by up to 10-15% in the dry season, whereas ρ_{terr} increases remain below 5% (Figure 5g,h).

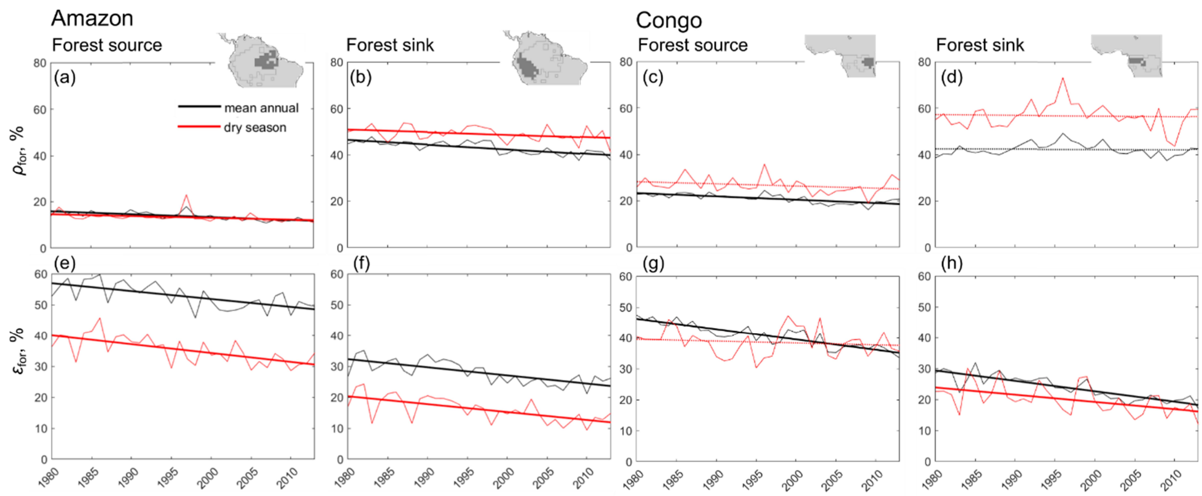

Figure 6. Trends in the percentage of rainfall from forest (ρ_{for}) and of evaporation contributing to forest rainfall (ε_{for}) in Amazon and Congo source and sink hotspot regions. Significant (p-value <0.05) linear trends in solid lines and non-significant trends are shown with dashed lines (i.e., dry season trend lines in c and g, and both mean annual and dry season trend lines in d).

In the Amazon forest, there has been a weak decrease over time in the fraction of rainfall reliance on forest moisture sources (ρ_{for}) (Figure 6ab) and a strong decrease in the fraction of forest evaporation that returns as rainfall over forest areas ($\varepsilon_{\mathrm{for}}$) (Figure 6ef). The decrease in dry season ρ_{for} in the Amazon sink hotspot is, however, considerably weaker than the decrease in mean annual ρ_{for}, contributing to an upward trend in dry season ρ_{for} anomaly. In absolute volumes, dry season anomaly in forest rainfall self-reliance has not changed significantly (Figure S7), while total mean annual P has increased and dry season P has stagnated (Figure S8). Although E in the Amazon forest has also increased, less E precipitates over the forest (Figure S7) and more of the increase in P originates from elsewhere.

In the Congo forest, no strong and significant trends could be observed for ρ_{for}. The downward trend for mean annual $\varepsilon_{\mathrm{for}}$ is, however, strong and significant in both Congo source and sink hotspots. Because the downward trend for dry season $\varepsilon_{\mathrm{for}}$ is weaker than the trend for mean annual ε_{for}, there is a downward trend in dry season ε_{for} anomaly. Also in absolute volumes, dry season anomaly in forest evaporation contribution to its own rainfall (E_{for}) decreased in both Congo source and sink hotspots (Figure S7), even though the increase in mean annual E has exceeded the increase in dry season E (Figure S8).

4.4 Correspondence and contrariety between E_{for} and E anomalies

To explore the role of forest E in supplying moisture to forest P during dry periods, we compare the forest E_{for} and E anomalies (where E_{for} is the evaporation that precipitates in areas with forest cover > 85%, and thus by mass conservation, the sum of E_{for} is equivalent to total forest P). Correspondence between E_{for} and E can indicate that the E anomaly drives and supports the E_{for} anomaly, whereas contrariety can indicate that the E anomaly acts to dampen the E_{for} anomaly. In other words, in case of contrariety, E_{for} anomalies are driven by wind changes and occur despite E anomalies of opposite sign (see Sect. 2.2.3 for methods description).

Dry-season and dry-year dry-season rainfall anomalies in both the Amazon and Congo are driven by E anomalies external to the rainforests, with almost no correspondence between forest E and E_{for}. In the Amazon, correspondence between dry season E anomalies and E_{for} anomalies mainly occurs in the Atlantic Ocean, whereas contrariety mainly occurs in the Amazon forest (Figure 7a). This highlights the role of the forest for buffering the negative E_{for} anomaly. Summing up the fraction of the contrariety over forest, other land, and oceans separately shows that forest is the largest contributor to contrarieties in negative JJAS E_{for} anomaly (Figure 7b). We further note that the forest contribution to the negative anomaly contrariety has increased significantly over time, while its contribution to negative anomaly correspondence has remained low (Figure S9ad). In terms of negative dry year anomaly, forest contrariety also sums up to more than a third of the total contrarieties (Figure 7c), mainly in the southern parts of the Amazon (Figure S10g).

In the Congo, E anomaly in forests and other land areas contradicts negative E_{for} anomaly in the JF dry season (Figure 7b,c). In the JJA season, however, land E appears to contribute to both the positive and negative E_{for} anomaly (Figure 7b), whereas ocean E anomaly contradict both negative dry season and dry year E_{for} anomaly (Figure 7b,c). The role of forests for negative dry season anomaly contributions and contrarieties has not changed as drastically as in the Amazon (Figure S9b,c,e,f). In the JJA dry season, forests have rather decreased their buffering of negative contrariety over time (Figure S9f). For spatial breakdown of the correspondence and contrariety components in Congo, see Fig. S11 and S12.

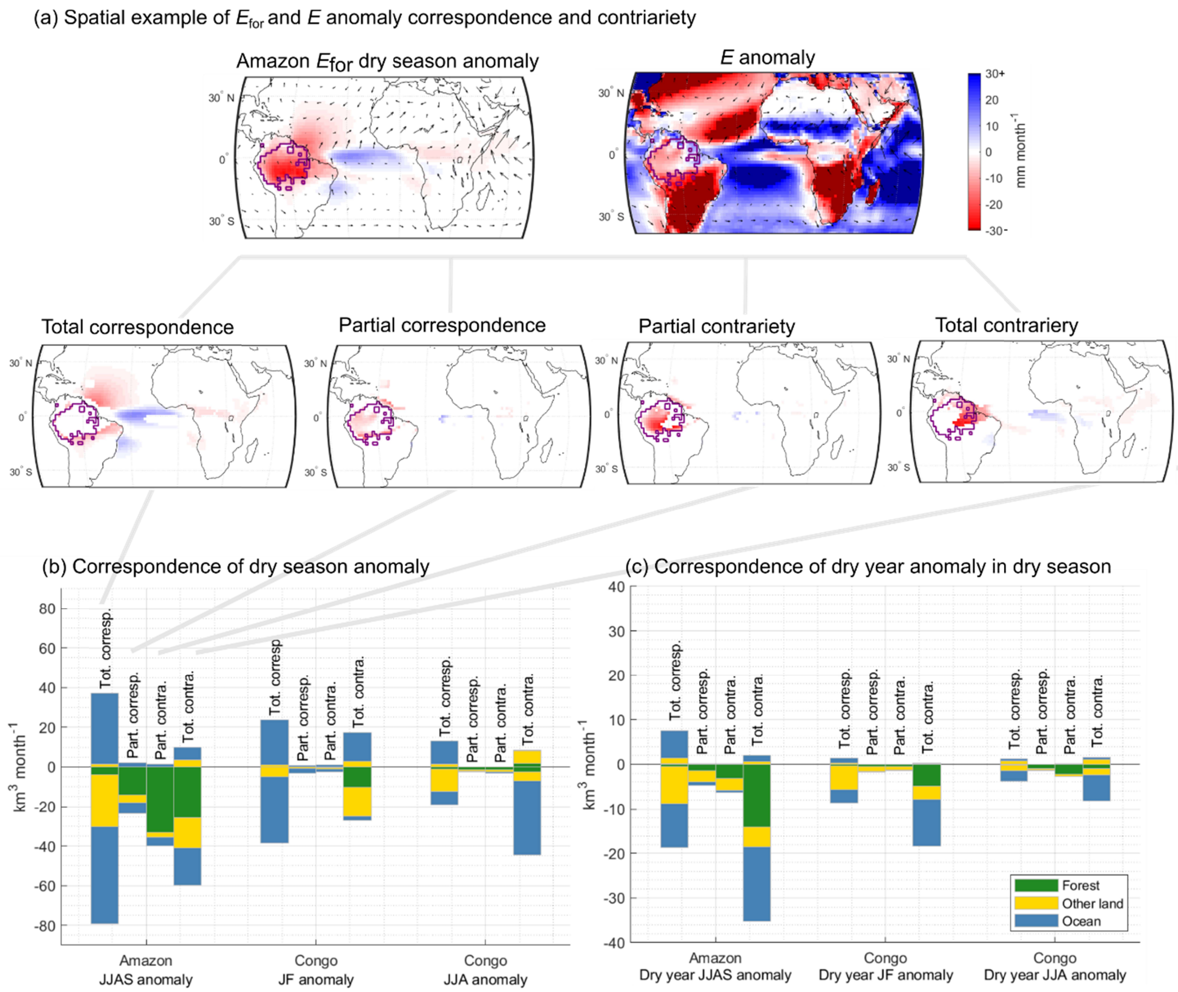

Figure 7. Breakdown of forest precipitation anomalies into its causes: correspondence (E_{for} and E anomalies agree in sign) and contrariety (E_{for} and E anomalies have opposite signs). (a) Spatial breakdown of the different components for the Amazon JJAS-mean E_{for} anomaly. The spatially distributed categories consist of forest, other land, and ocean for both Amazon and Congo for the (b) dry season anomalies, and (c) dry-years dry-season anomalies. Calculations are explained in Sect. 2.2.3.

4.5 Dry season amplification of countries' forest moisture reliance

Countries' reliance on rainforest moisture during dry seasons can differ considerably from their mean annual reliance (Figure 8a,b). The biggest absolute differences between country-scale mean annual and dry season ρ_{for} in South America are found in Bolivia, Paraguay, Uruguay, Brazil, Ecuador, and Peru (in the order of declining difference, Figure 8a). For example, Bolivia depends on the forest for 23% of its mean annual precipitation, but 35% of its dry year JJAS precipitation; and Paraguay doubles its forest moisture reliance going from 9% at mean annual scale to 19% during the JJAS season in dry years.

In Africa, the biggest dry season anomalies are found in Congo, Gabon, Equatorial Guinea, Democratic Republic of Congo, Guinea, Liberia, Sierra Leone, Cameroon, CAR, and Angola (in the order of declining difference, Figure 8b). For example, both Congo and Gabon receives around a third of their mean annual precipitation from the rainforest, but around half of their precipitation during the JJA dry season originates as forest moisture. In Guinea and Sierra Leone, ρ_{for} is negligibly low (1-2%) at a mean annual scale, but considerable during the dry seasons (7-9%).

Furthermore, the countries that host the largest areas of rainforests are not necessarily the countries that are most dependent on rainforest moisture supply for their rainfall, due to the forest's upwind positions. In South America, the country that hosts the largest rainforest areas is Brazil. However, Peru, Ecuador, Bolivia, Colombia, and Venezuela have a higher mean annual rainfall reliance on the Amazon forest than Brazil. In the dry season and dry years, Paraguayan precipitation has a similar forest moisture reliance as that of Brazil (Figure 8a). Similarly, in Africa, the Democratic Republic of Congo (DRC) is less dependent on the Congo rainforest for its precipitation than Gabon, Congo, and Equatorial Guinea, despite hosting the largest area of forest (Figure 8b).

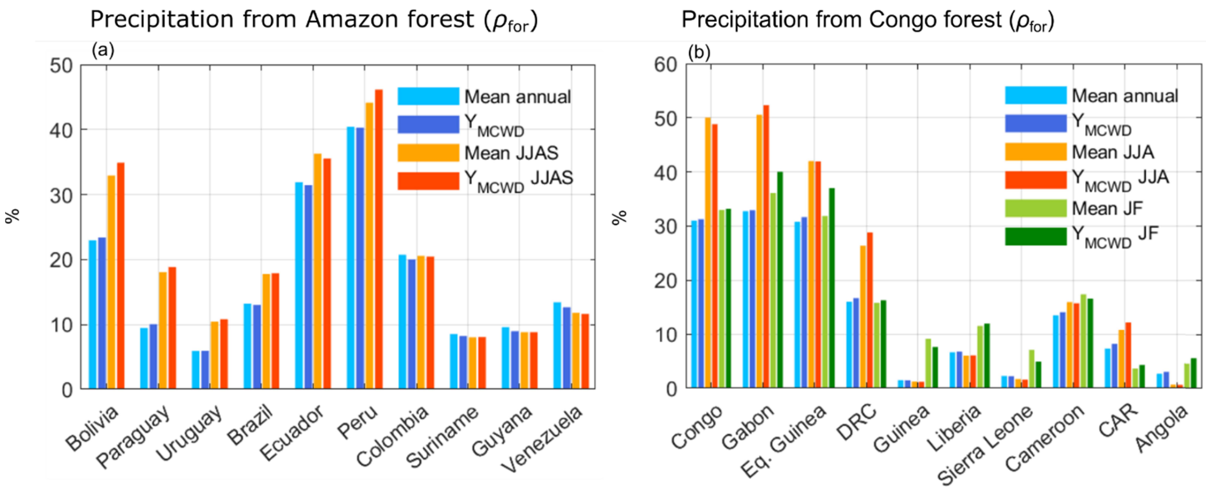

Figure 8. Percentage of country-level precipitation coming from a) Amazon and b) Congo forest evaporation. Ten countries are shown in the order of declining maximum difference between mean annual and dry season ρ_{for}. CAR stands for the Central African Republic, and DRC stands for the Democratic Republic of Congo.

5 Discussion

5.1 Amplification of forest precipitation recycling during dry periods

We examined the mean year and dry year dry season anomalies of moisture sources and sinks of forest *P* and *E* in the Amazon and Congo region based on 34 years of data and simulations. We selected the driest periods in the rainforests in order to understand moisture recycling variability when it is most critical for forest mortality and resilience. We find that forest precipitation recycling during dry seasons amplifies and increases the ratio of forest *P* originating from forest *E* in both the Amazon and Congo. This relative seasonal increase in forest precipitation recycling increases further in dry years.

We found that the dry period forest rainfall dependency increases more in the Congo than in the Amazon, and is substantially more important than the amplification of moisture supply from other terrestrial sources. In the Amazon, the relative moisture contribution from both terrestrial areas and the forest increases during the dry season (i.e., 13% increase in ρ_{terr} and 7% in ρ_{for}), and increases further by 3-4% in dry years (Table 1). In the Congo, both the dry season (JJA) and the dry year amplification is substantially larger for moisture sources from the forest itself than from terrestrial sources in general (see Sect. 4.1).

Furthermore, we found that the relative dry season anomaly of ρ_{terr} and ρ_{for} (Amazon and Congo boreal summer, but not Congo JF dry season) tends to be *higher* in regions with high mean annual ρ_{terr} and ρ_{for}, while the dry year dry season anomalies tend to be *lower* in regions with high mean annual ρ_{terr} and ρ_{for} (see Sect. 4.2). Both mean-years dry-season and dry-year dry-season anomalies are, however, largely positive across the forest region. In other words, forest areas that have a generally high reliance on their own moisture supply for rainfall tend to increase that dependence more than other forest regions during dry seasons. In dry years, the positive anomalies further increase, but less than in forest areas with lower mean annual ρ_{terr} and ρ_{for}.

The dry season anomalies in rainfall self-reliance are likely to continue to be relevant given current trends. In the Amazon forest, the dry season anomaly of rainfall self-reliance has increased in the Amazon sink hotspot, because dry season ρ_{for} declined less than mean annual ρ_{for}, possibly partly because overall dry season precipitation has not increased during the study period. Under future climate, global models project that recycling ratios over the Amazon and Congo basin will decline (Baker & Spracklen, 2022; Findell et al., 2019). However, it is unclear if this will affect the role of forest supply under for example increased severity, frequency, and duration of droughts, or increase in dry season length (Khanna, Medvigy, Fueglistaler, & Walko, 2017; Marengo et al., 2011). Dry season forest supply will also depend on the overall effects of a variety of forest responses (e.g., mortality, rooting depth adaptation) to environmental stressors that are not well captured in climate models (Schewe et al., 2019). In the Congo forest, rainfall self-reliance does not show any significant trend, but has more interannual variability than in the Amazon (Figure 6).

Our estimates of increases in forest rainfall self-reliance during dry season and dry years in the Amazon compares well with many others studies (Table S2). For example, Zemp et al. (2014) similarly found 1-2 percentage point increase in the precipitation recycling ratio in the Amazon basin during the dry seasons compared to the mean annual, and a weak 1 percentage point weakening in precipitation recycling was found by Chug, Dominguez, & Yang, (2022). Others found more considerable amplification of precipitation recycling. For example, Staal et al. (2018) found an increase of ~10 percentage point increase, in 2005 and 2010 during the dry season in northwestern Amazon. Bagley et al. (2014) found a 7 percentage point increase in dry season Amazon rainfall self-reliance during the 2005 and 2010 drought years in comparison to wet years, similar to e.g., findings of Mu, Biggs, & De Sales (2021). However, our findings differ considerably from the conclusions of Satyamurty et al., (2013), who found recycling to be lower in dry seasons. Their recycling estimate assumed that any moisture that is not converged constitutes recycled precipitation, although in reality, the outgoing flux may comprise both locally evaporated moisture and atmospheric water passing through. Thus, their estimates constitute an upper limit to recycling that is not directly comparable to ours. Our study also suffers from limitations, such as a relatively coarse spatial resolution and use of only two atmospheric layers, which does not allow us to capture smaller-scale atmospheric circulation. Future studies could also consider analyzing the dry season for different parts of the Amazon forests separately, as e.g., parts of the northern Amazon have the opposite seasonality than that of the rest of the Amazon (Fisch et al., 2004).

Differences in study region selection are likely another major cause of discrepancy when comparing among studies (see Table S2), more so in the Congo region due to the considerable mismatch in the extent of the Congo rainforest extent and the Congo basin. Depending on region selection and methods, mean annual ρ_{for} vary between 28% and 68% in different studies (see Table S2; e.g., Dyer et al., (2017); te Wierik, Keune, Miralles, & Gupta, (2022)). For example, Sorí et al. (2017)'s analysis of the Congo river basin found that internal basin precipitation recycling decreases in dry seasons and dry years despite increases in evaporation. However, Pokam et al., (2012), who analyzed moisture recycling over a study region better approximating the forest region, arrived at a conclusion more similar to ours: that precipitation recycling ratio increases in the dry season. This sensitivity of precipitation recycling estimates to study region selection in Central Africa may be attributable to both heterogeneity in land-cover type, and seasonal shifts in circulation patterns modulated by a latitudinal gradient in sea surface temperature in the Indian Ocean (Dyer et al., 2017).

5.2 High forest evaporation rates help explain dry period increase in ρ_{for}

We conclude that high dry period forest evaporation has an important role in increasing dry period ρ_{for}. In Sect. 4.2, we found that forest rainfall self-reliance occurs despite decreases in ε_{for}, i.e., the fraction of forest E that returns as forest P. This seemingly paradoxical situation arises because ε_{for} decrease comparatively less during a dry period (Sect. 4.3) and the drastic dry period decrease in P is compensated and counter-acted by increasing or unchanging forest E as it is energy-limited rather than water limited (Baker et al. 2021). The same response was found during the onset of the Western European drought in 2018, where initially evaporation was also not water limited (Al Hasan, Link, & van der Ent, 2021; Benedict et al., 2021). The enhanced role of forest evaporation during dry season can also be due to a higher sensitivity of precipitation to atmospheric moisture content change below certain levels (Baudena et al., 2021). In Sect. 4.4, we explicitly compared the dry period anomalies of E_{for} and E, and found that E anomalies in forests and other terrestrial areas dominate the contrariety with negative dry period anomalies E_{for} in the Amazon and Congo boreal summer dry seasons. In other words, positive E dry period anomalies in forests and other terrestrial areas act to dampen negative, wind-driven E_{for} anomalies. This indicates that high dry period forest E rates, in fact, *counteract* wind-driven anomalies to support dry period increase in ρ_{for}.

The anomaly correspondence-contrariety analysis method introduced here differentiates how E anomalies contribute to the amplification or dampening of E_{for} anomalies. Future applications of the method could, for example, shed light on the role of E anomalies for E_{for} anomalies during heatwaves, under climate change, or land cover change, as an addition to current methods such as correlation analyses (O'Connor et al., 2021; Pranindita, Wang-Erlandsson, Fetzer, & Teuling, 2022) and coupled model simulations under different scenarios (Swann, Longo, Knox, Lee, & Moorcroft, 2015). In addition, distributed or lumped versions of E_{for} and E anomaly correspondence and contrariety also help highlight the need to understand both P source and E sink, as one-sided analyses of P source are unable to explain the respective role of E and wind anomalies in driving anomalies in moisture source reliance.

5.3 Potential implications for forest governance

Increasingly, policies to promote nature-based solutions to address climate change such as forest restoration and conservation are being proposed, planned and implemented (Chaplin-Kramer et al., 2019; Griscom et al., 2017). The benefit of forest moisture supply for forest resilience, agriculture, and water resources are increasingly recognized (Cui et al., 2022; Hoek van Dijke et al., 2022; Leite-Filho et al., 2021). At the same time, dry season length in both the Amazon and Congo forests is increasing (Fu et al., 2013; Jiang et al., 2019) and rainforests are becoming increasingly vulnerable to repeated droughts (Tao et al., 2022). Thus, it will be important to understand where measures to prevent deforestation or promote forestation might have the greatest benefits for counteracting such drying trends (Obbe A. Tuinenburg, Bosmans, & Staal, 2022). In Congo, the dependency of forest rainfall on terrestrial evaporation (ρ_{terr} is 64%, and ~70% in dry seasons) is much higher than the dependence on forest evaporation (ρ_{for} is 28%, and ~30-40% in dry seasons), indicating that substantial land areas without dense forests are also important for moisture supply to rainfall. Such differences are also found in the Amazon, although differences are smaller (at the mean annual scale, ρ_{for} = 26%, ρ_{terr} = 42%). Compared to the Amazon, the Congo rainforest is also projected to face greater future threats of forest loss and greater deforestation impacts on regional precipitation (Smith, Baker, & Spracklen, 2023).

The need for governance of moisture flows is increasingly being discussed in the scientific literature (Keys, Wang-Erlandsson, Gordon, Galaz, & Ebbesson, 2017; te Wierik, Gupta, Cammeraat, & Artzy-Randrup, 2020). Hitherto, most analyses of moisture flows at the country scale focus on the mean annual scale (Dirmeyer, Brubaker, & DelSole, 2009; Keys et al., 2017). Here, the analyses (Sect. 4.5) show that dry period amplification of forest moisture reliance can be very high. For example, in the case of Guinea and Sierra Leone, countries' rainfall reliance on forest moisture grow from negligible (1-2%) at the mean annual scale to substantial (7-9%) in the dry season. This means that the consideration of forests' importance for different nations' management and governance contexts will need to go beyond the mean annual scale and account for seasonal variations.

6 Conclusions

To conclude, we found an increase in the role of forest evaporation for buffering against forest rainfall reductions during dry seasons and further during dry years. High dry period forest evaporation enables forests to rely on their own moisture supply for rainfall, despite a decreasing fraction of forest evaporation that contributes to forest rainfall. In the forest areas with the highest reliance on forest moisture supply, dry season amplifications of forest precipitation recycling ratios tend to be larger than elsewhere. We conclude that dry period amplification of precipitation recycling ratios highlights additional risks of loss of forest resilience from deforestation as well as opportunities in resilience building from forest conservation and restoration. As such, accounting for an enhanced forest rainfall self-reliance in dry periods can be essential for understanding the combined impact of deforestation and climate change on forest resilience.

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Open Research

The ERA-Interim reanalyses data used in this study can be downloaded at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim. Precipitation data from MSWEP can be obtained here: http://www.gloh2o.org/mswep/. The corresponding WAM-2layers code in Python is available at https://github.com/ruudvdent/WAM2layersPython. The data of tracked precipitation and evaporation of the forest regions in this study are downloadable at https://doi.org/10.5281/zenodo.7635445.

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