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Divergent Representation of Precipitation Recycling in the Amazon and the Congo in CMIP6 Models

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Key Points:

- This study quantifies, for the first time, precipitation recycling ratios over the Amazon and Congo Basins in Coupled Model Intercomparison Project Phase 6 models
- Seasonal recycling is well represented in the Congo but there is a large-scale underestimation in the Amazon dry-to-wet transition season
- These findings have implications for model representation of land-use change impacts in the Amazon

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Moisture evaporated from the land contributing to precipitation in a given area is known as precipitation recycling and needs to be accurately represented in climate models. The Amazon and Congo basins are reported to have the highest precipitation recycling rates globally, but model representation has not yet been assessed over these regions. We evaluated recycling over the Amazon and Congo in 45 Coupled Model Intercomparison Project Phase 6 models. Regional annual means from models and reanalyzes agreed well over both basins. Models captured seasonal variation in recycling over the Congo but there was a large-scale underestimation of recycling during the Amazon dry-to-wet transition season relative to ERA5, caused by models underestimating Amazon evapotranspiration and overestimating incoming wind speed and associated water vapor imports. Both regions show robust declines in precipitation recycling over the next century under future climate-change scenarios. Our results suggest models may underestimate impacts of deforestation on regional precipitation in the Amazon.

Plain Language Summary In the Amazon and Congo basins, much of the rain that falls to Earth is transferred back to the atmosphere through evaporation over tropical forests, providing essential moisture for further rainfall events downwind. This process of rainfall recycling, which is vital for sustaining the rainforest, is disrupted when forest is cut down. For researchers to understand how deforestation in the Amazon and Congo might impact the climate it is vital that climate models accurately represent the fraction of rain coming from recycled moisture. Our study found that models represented rainfall recycling relatively well in the Congo, but underestimate recycling in the Amazon dry-to-wet transition season. This is important because it could mean these models underpredict the influence of deforestation on climate in the Amazon.

1. Introduction

Moisture for precipitation over a particular area can either originate from evapotranspiration (E) within the area, or from water vapor transported from elsewhere (Brubaker et al., 1993; Eltahir & Bras, 1994; Gimeno et al., 2012; Trenberth, 1999). The ratio of locally-derived to total precipitation is known as the precipitation recycling ratio and provides a method of quantifying the land-surface contribution to regional precipitation. Areas with high precipitation recycling are expected to show greater climate sensitivity to land-use change, such as tropical deforestation, due to the effects on surface water fluxes and downwind precipitation (Eltahir & Bras, 1996; Spracklen et al., 2012). In order to accurately simulate the regional climate impacts of land-use change, climate models must provide an accurate representation of precipitation recycling in areas where: (a) precipitation recycling is known to be important, and (b) where deforestation rates are high.

The Amazon and Congo river basins are reported to have the highest precipitation recycling rates globally (Tuinenburg et al., 2020). These regions contain extensive areas of tropical forest (Saatchi et al., 2011), characterized by high rates of E, which, combined with prevailing winds, allow moisture to be propagated thousands of kilometers inland (Salati et al., 1979; Spracklen et al., 2018; Staal et al., 2018; van der Ent et al., 2010). The Amazon hydrological cycle is characterized by a single wet season with precipitation peaking during the austral summer (December–February, DJF, Marengo, 2006), while the Congo basin has two rainy seasons, with peaks in March and November (Crowhurst et al., 2021). A literature survey for this study (Table S1 in Supporting Information S1) found annual-mean recycling estimates for the Amazon ranging from 24% to 41% (Brubaker et al., 1993; Burde et al., 2006; Costa & Foley, 1999; Eltahir & Bras, 1994; Staal et al., 2018; Trenberth, 1999; Tuinenburg et al., 2020; van der Ent et al., 2010; Yang & Dominguez, 2019; Zemp et al., 2014) compared to 28%–50% for the Congo (Dyer et al., 2017; Pokam et al., 2012; Sorí et al., 2017; Tuinenburg et al., 2020). The spread in recycling estimates reported for the Amazon and Congo can be attributed to differences in the modeling approaches used, variation in inputs, analysis domain boundaries, and quality of the input data (Zemp et al., 2014).

Rates of forest loss for the Amazon and Congo are among the highest in the world (Hansen et al., 2013; Potapov et al., 2017; Tyukavina et al., 2018). Primary forest loss for the Amazon and Congo from 2002 to 2019 was estimated at 30.5 and 6.1 Mha, respectively, equivalent to 0.31% and 0.19% yr^{-1} (Butler, 2020; Hansen et al., 2013). Historical and future forest loss is projected to reduce regional precipitation through a reduction in precipitation recycling over the two basins though results vary widely among modeling studies (see Lawrence & Vandecar, 2015; Perugini et al., 2017; Spracklen & Garcia-Carreras, 2015; Spracklen et al., 2018 and references therein). In addition to variation in simulation setup, differences between model land-surface schemes and parameterization of sub-grid scale processes have been suggested to be important in driving these differences (Bell et al., 2015; Crowhurst et al., 2020). However, representation of precipitation recycling over the Amazon and Congo in global climate models has not previously been assessed.

In this study we make a first attempt to assess the representation of regional precipitation recycling over the Amazon and the Coupled Model Intercomparison Project Phase 6 (CMIP6) models. Our results provide insights on the ability of CMIP6 models to represent the land-surface contribution to rainfall over two important regions of tropical forest, with implications for their representation of land-use change impacts on climate.

2. Data and Methods

2.1. CMIP6 Model Output

We analyzed precipitation recycling using output from 45 global climate models contributing to CMIP6 (Eyring et al., 2016; Table S2 in Supporting Information S1). Monthly model output available in March 2021 was downloaded from the World Climate Research Program Earth System Grid Federation. We retrieved historical simulations (1979–2014) and simulations from four future Shared Socioeconomic Pathway (SSP) experiments representing alternative development scenarios over the next century. These can be approximately interpreted as low (SSP1-2.6), medium-low (SSP2-4.5), medium-high (SSP3-7.0) and high (SSP5-8.5) radiative-forcing levels by 2100 (O'Neill et al., 2017). In terms of land-use change, the SSP3-7.0 scenario has the largest reduction in forest cover over the next century, SSP5-8.5 scenario has relatively little change, and forest cover increases in the future under the SSP1-2.6 and SSP2-4.5 scenarios (Lawrence et al., 2016). We selected models that provided historical simulations of the following variables (Table S3 in Supporting Information S1): three-dimensional specific humidity (q, kg kg^{-1}), zonal (u) and meridional (v) wind fields (m s^{-1}), evapotranspiration (E, kg m^{-2} s^{-1}), precipitation (kg m^{-2} s^{-1}) and surface temperature (K). When available, multiple realizations were used to derive an ensemble mean to remove the influence of random error and uncertainty associated with initial conditions (e.g., Krasnopolsky & Lin, 2012; Palmer et al., 2004).

2.2. Reference Data

Calculation of precipitation recycling requires consistent representation of the atmospheric moisture budget; thus, reanalyzes were used to evaluate model performance (Text S1 and Table S4 in Supporting Information S1). We compared the Amazon and Congo seasonal cycles in E and P from each reanalysis with independent datasets to assess whether the processes used to derive E and P are likely to be realistic (Text S2 in Supporting Information S1). The catchment-balance approach provides data-driven, independent estimates of E (Baker et al., 2021; Burnett et al., 2020), and a merged satellite-rain gauge product (CHIRPS2, Funk et al., 2015) was used to evaluate precipitation. Based on these results, only ERA5 (Hersbach et al., 2020) and JRA-55 (Kobayashi et al., 2015) were used to evaluate CMIP6 models at the seasonal timescale, with ERA5 selected as the primary reference data set since it showed the strongest correlations across both regions (Table S5 in Supporting Information S1). An important caveat is that reanalyzes, including ERA5, do not fully capture the strong seasonality in Amazon E that the catchment-balance E estimates indicate (Baker et al., 2021). However, since we draw consistent conclusions when comparing Amazon CMIP6 E to ERA5 and catchment-balance E, we do not expect the underestimation of Amazon E seasonality in ERA5 to affect the main conclusions that we draw in this study.

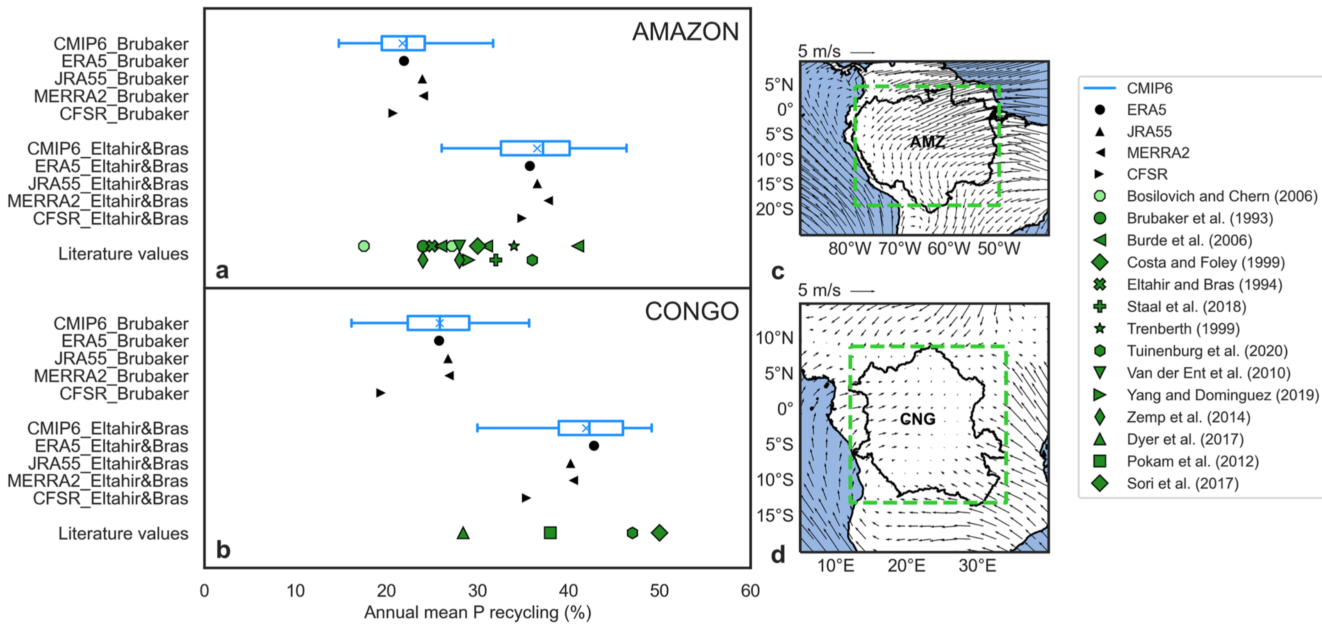

Figure 1. Annual mean precipitation (P) recycling estimates for (a) the Amazon and (b) the Congo from 45 Coupled Model Intercomparison Project Phase 6 models (blue boxplots) and four reanalyzes (black markers) calculated in this study using the Brubaker model and the EB94 model (data from 1979 to 2014), compared against values from the literature (green markers). Climatological annual-mean lower-tropospheric (1000–850 hPa) winds from ERA5 (vectors) and the domains used for each basin (green boxes) are shown in panels (c and d). Box plots show the quartiles (box), mean (x marker) and the upper and lower extremes (whiskers). Note that the literature values from Bosilovich and Chern (2006) are for October–December only and shown in a different color (light green circles).

2.3. Precipitation Recycling

Monthly precipitation recycling was estimated for the Amazon (19°S–5°N, 79°W–50°W) and Congo (13°S–9°N, 12°E–34°E). These domains were chosen to capture the entirety of the river basin in each region (Figures 1c and 1d). To estimate recycling we applied the models from Brubaker et al. (1993) and Eltahir and Bras (1994, henceforth EB94). These are both examples of "bulk" recycling models, and were selected because they are relatively computationally simple (Bosilovich & Schubert, 2002), making them an appropriate choice for a multi-model comparison study. Although we observed some differences in the magnitude of recycling ratios derived from the two approaches, results at the seasonal timescale showed good agreement. For brevity, we describe the EB94 model in this section and provide a description of the Brubaker model in Text S3 in Supporting Information S1.

The EB94 method provides insights on the spatial variation in recycling and has been shown to compare well to more sophisticated models that include water vapor tracers (Dominguez et al., 2022). Calculations are performed at the grid-cell level using an iterative approach to derive the precipitation recycling ratio ($\boldsymbol{\rho}$). The model requires E plus column-integrated moisture fluxes (qu and qv, kg m^{-1} s^{-1}), calculated as mass-weighted vertical integrals (Text S4 in Supporting Information S1). Moisture fluxes across the domain are decomposed into moisture that originated from within the domain (i.e., of local origin) and fluxes that originated externally. For each grid cell, $\boldsymbol{\rho}$ is the ratio of moisture outflux of local origin ($\boldsymbol{O}_{\mathbf{local}}$) to total outflux ($\boldsymbol{O}$), which is equal to the ratio of local precipitation ($\boldsymbol{P}_{\mathbf{local}}$) to total precipitation ($\boldsymbol{P}$):

$$\frac{O_{\text{local}}}{O} = \frac{P_{\text{local}}}{P} = \rho \tag{1}$$

Rearranging Equation 1:

$$O_{\text{local}} = O \times \rho \tag{2}$$

In practice, ρ is initially guessed for each grid cell and used to compute O_{local}. O_{local} for one grid cell is the incoming moisture of local origin (I_{local}) for an adjacent grid cell, allowing ρ values for each cell to be recalculated iteratively, using the prior ρ estimates of the surrounding grid cells to determine the local moisture fluxes (with total O derived directly from qu and qv):

$$\rho^{(n+1)} = \frac{\rho^{n} \times O + e}{O + e} = \frac{I_{\mathrm{local}} + e}{I + e} \tag{3}$$

where n is the iteration number and e is the evapotranspiration over the grid cell multiplied by the cell area in metres. Eltahir and Bras (1994) showed that recycling values quickly converge using this approach. All datasets were re-gridded to that of the coarsest-resolution model (2.8125° × 2.8125°) before computing recycling ratios.

The recycling models applied here assume a well-mixed atmosphere, which may not be valid over areas of moist tropical forest. Lettau et al. (1979) described the "fast recycling" that occurs over the diurnal cycle in the Amazon, with local clouds developing and raining out before evaporated moisture has fully mixed through the atmospheric column. The well-mixed assumption could mean that recycling is underestimated. Another caveat is that Equations 1 and 2 were applied to monthly data, neglecting the transient eddy contribution to water vapor fluxes, potentially causing a slight underestimation of recycling values (Text S5 and Figure S1 in Supporting Information S1). In this study, we were primarily interested in benchmarking recycling in models against reanalyzes and found good agreement between our EB94 results and those from the literature (Figure 1).

3. Results and Discussion

Annual-mean ρ values for the Amazon and Congo estimated from models and reanalyzes are compared with literature values in Figure 1. For both recycling approaches, CMIP6 values agree well with reanalyzes, though estimates from the Brubaker method are lower than the EB94 estimates, which are more consistent with previously-reported values. Mean Amazon ρ from the CMIP6 ensemble using the EB94 method is 36.5 ± 4.9% (mean ± standard deviation), which is very close to the mean of the reanalyzes (36.2 ± 1.2%, Figure 1a, c.f. 18.7 ± 3.3 vs. 21.6 ± 1.5 from the Brubaker method, Table S6 in Supporting Information S1). In the Congo, annual-mean ρ estimates are higher than in the Amazon, and CMIP6 models and reanalyzes agree relatively well (Figure 1b). The Congo CMIP6 mean from EB94 is 41.9 ± 4.9% and the reanalysis mean is 39.7 ± 3.1%. Our results confirm the expectation that the Brubaker method may underestimate the true magnitude of recycling in the Amazon and Congo Basins, while the EB94 method is likely to be more accurate. In the Amazon, CMIP6 mean recycling of 18.7 ± 3.3 from the Brubaker method lies well below the mean of literature values (29.8 ± 5.0%, Table S1 in Supporting Information S1), while CMIP6 mean recycling of 36.5 ± 4.9% from the EB94 method is closer to literature values. Similarly, in the Congo, mean CMIP6 recycling of 28.4 ± 11.4% from the Brubaker method lies well below the mean of literature values (40 ± 11%), while mean recycling of 41.9 ± 4.9% from EB94 is more consistent. Given the better performance of EB94 relative to literature values, we focus the rest of our discussion on presenting results from this model and provide results from the Brubaker method in Supporting Information S1.

Spatial variation in ρ over the Amazon and Congo basins in each season is shown in Figure 2. In the Amazon, models capture a gradient in recycling across the basin, with the highest values in the western margins (Figure 2, columns 1 & 2). However, CMIP6 models show a spatially coherent underestimation of Amazon recycling in June–August (JJA, Figure 2o) and September–November (SON, Figure 2u), relative to ERA5. In SON, negative ρ biases are observed across 70% of the basin and by the majority of models (Figure 2u). During DJF and March–May, CMIP6 models simulate higher ρ than ERA5 over the Amazon, with the biases in different parts of the year compensating to result in comparable regional annual means (Figure 1).

In the Congo, recycling is highest in the southeast during DJF (Figure 2d) and in the northern basin in JJA (Figure 2p), and this spatial pattern is well replicated by the models (Figures 2e and 2q). CMIP6 models show a negative bias relative to ERA5 in the central northern Congo in JJA (Figure 2r), though in general models show less agreement in the direction of biases over the Congo compared to the Amazon (less stippling in Figure 2), and biases are less spatially extensive, suggesting that the CMIP6 ensemble mean generally represents recycling better over the Congo than over the Amazon at the seasonal scale.

Climatological seasonal cycles in ρ and its controlling variables for the whole Amazon and Congo are presented in Figure 3. In the Amazon, ERA5 and JRA-55 show annual peaks in ρ in SON of 41.2% and 42.3%, respectively,

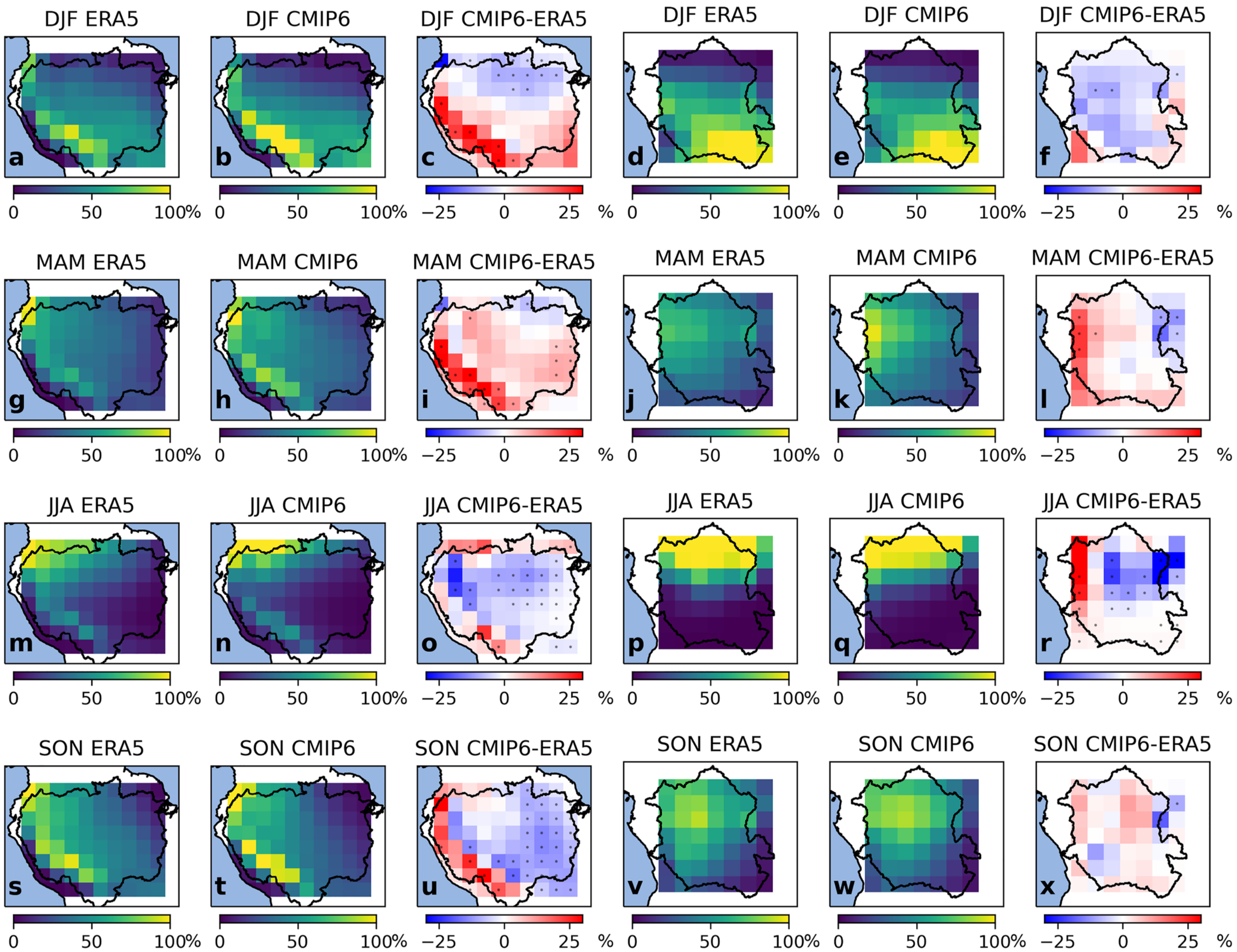

Figure 2. Spatial variation and absolute differences in ρ in ERA5 and the Coupled Model Intercomparison Project Phase 6 ensemble mean over the Amazon and Congo for (a–f) December–February, (g–l) March–May, (m–r) June–August, and (s–x) September–November. Recycling was estimated for 1979–2014 using EB94, with grid-cell values weighted by normalized precipitation. Stippling indicates where at least 75% of the models agree on the direction of biases relative to ERA5. Relative difference maps are shown in Figure S2 in Supporting Information S1.

compared to 38.8% for the CMIP6 models (Figure 3a; 26.7% and 28.1% vs. 22.4% in Brubaker estimates, Figure S3a in Supporting Information S1), consistent with biases shown in Figure 2u. Less than half (20/45) of CMIP6 models captured a statistically significant positive correlation with the ERA5 Amazon seasonal cycle (Table S7 in Supporting Information S1), with the ensemble-mean showing the highest ρ in March (Figure 3a). The underestimation of E (relative to both ERA5 and catchment-balance) and overestimation of moisture influx (relative to ERA5) both contribute to the CMIP6 underestimation of Amazon ρ in SON (Figures 3b and 3c). The CMIP6 underestimation of recycling relative to ERA5 shown in Figure 3a is likely to be a conservative estimate, since ERA5 does not capture the strong dry-season increase in E indicated by catchment-balance (Figure 3b, Text S2 in Supporting Information S1). Correlations indicate that seasonal variation in Amazon ρ is primarily controlled by E but this is not captured by the models (Table S8 in Supporting Information S1).

The combination of CMIP6 models underestimating E and simulating excess advected moisture results in the land-surface contribution to precipitation being underestimated in SON, which represents the transition between the dry and wet seasons in the Amazon (Figure S4a in Supporting Information S1). Previous studies have shown Amazon deforestation has the greatest impact on climate at the end of the dry season, as forest loss reduces the transfer of deep groundwater to the atmosphere by transpiration (Baker & Spracklen, 2019; da Rocha et al., 2004; Davin & de Noblet-Ducoudré, 2010; von Randow et al., 2004). Furthermore, the underestimation is concentrated

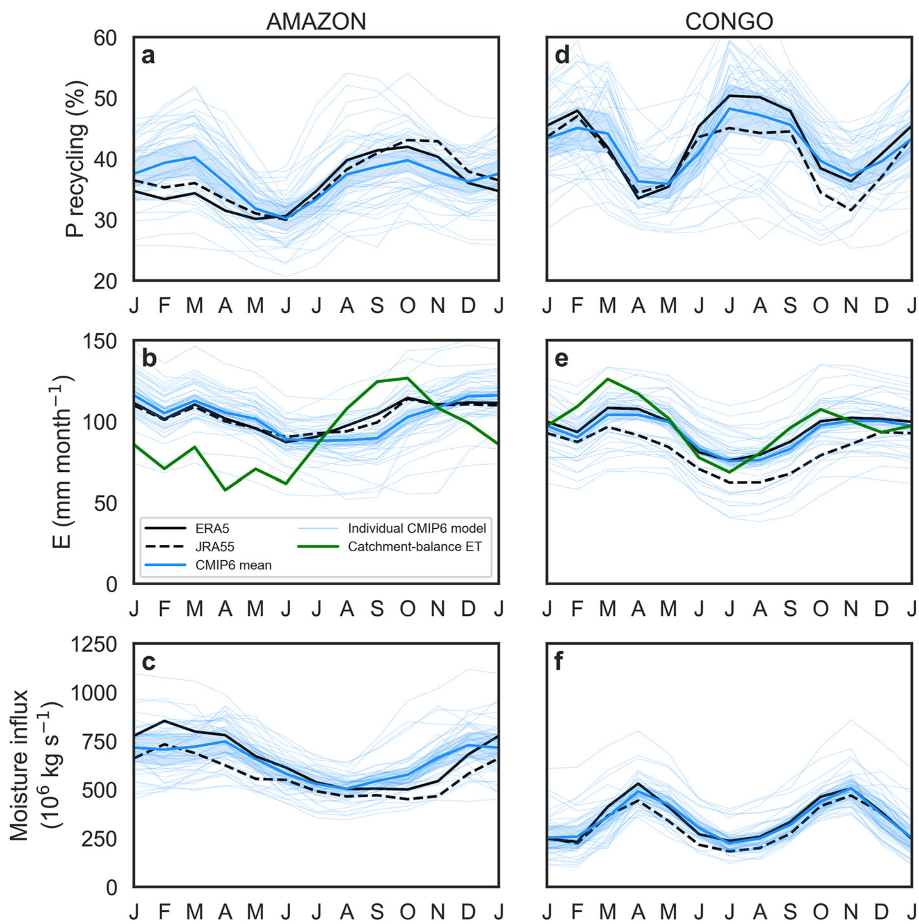

Figure 3. (a and d) Seasonal variation in precipitation (P) recycling estimated using EB94; (b and e) domain-average evapotranspiration (E); and (c and f) moisture influx, over the Amazon and Congo basins calculated using two reanalyzes (black lines) and 45 Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models (narrow blue lines) using data from 1979 to 2014. The CMIP6 ensemble mean and interannual standard deviation are shown by the thick blue line and blue shading, respectively. Independent catchment-balance E estimates for the Amazon (Baker et al., 2021) and the Congo (Burnett et al., 2020) are indicated in green in panels (b and e). The catchment-balance E estimates are from 2003 to 2013 (Amazon) and 2002 to 2016 (Congo). The domains used for each basin are indicated by the green dashed boxes in Figures 1c and 1d.

in the eastern Amazon (Figure 2u), which is important because the southeast of the basin is a deforestation hotspot (Hansen et al., 2013), and it is therefore crucial that models accurately represent land-atmosphere interactions in this region. These results have implications for analyses of deforestation impacts on future precipitation, since in the models a smaller fraction of rainfall is derived from the land surface than in reality. This could result in CMIP6 models underestimating the impacts of Amazon land-use change on climate in future scenarios.

In the Congo, CMIP6 models show relatively good agreement with reanalyzes (Figure 3d), with three quarters (33/45) showing statistically significant positive correlations with ERA5 at the seasonal scale (Table S7 in Supporting Information S1). The spread across reference datasets is higher in the Congo than in the Amazon (Figures 1b and 2), reflecting more-limited in situ observations to assimilate and constrain the reanalyzes over this region (e.g., Haiden et al., 2018). CMIP6 models capture a bimodal distribution in ρ with peaks during the drier parts of the year (JJA and DJF). Results from both recycling approaches were found to be consistent (Figures 3d, S3b, and S4b in Supporting Information S1). The correspondence between E estimates from catchment-balance, reanalyzes and CMIP6 models shown in Figure 3e suggests that the simulated seasonal cycle in Congo E is relatively robust. E, which might be expected to positively correlate with ρ, broadly follows the same seasonal cycle as precipitation in the Congo (Figure S4b in Supporting Information S1), providing essential atmospheric moisture without being the primary driver of precipitation seasonality (Cook & Vizy, 2021). An imbalance in E between the two rainfall peaks has been linked to a difference in solar radiation (Burnett et al., 2020; Crowhurst et al., 2021; Crowhurst et al., 2020). Our results indicate the seasonal cycle of ρ in the Congo is most strongly influenced by variation in moisture influx (Figure 3f), with strong statistically-significant negative correlations between ρ and influx in reanalyzes and CMIP6 models ($r = -0.88$–-0.93, $p < 0.001$, Table S8 in Supporting Information S1).

To further understand representation of precipitation recycling in CMIP6 models, we decomposed advected moisture into its component fields, that is, wind and specific humidity (Hari et al., 2020). In the Amazon, models overestimate winds in the lower troposphere (1000–850 hPa, Figure S5a in Supporting Information S1), which is the height in the atmosphere with the highest humidity content and most important for moisture transport (Ralph et al., 2005). Since models represent incoming humidity relatively well (Figure S5b in Supporting Information S1), this causes an overestimation of moisture imports to the Amazon. In the Congo, CMIP6 models also overestimate lower troposphere incoming winds (Figure S6a in Supporting Information S1), though a compensating underestimation of incoming humidity (Figure S6b in Supporting Information S1) results in adequate representation of moisture imports (Figure 3f). This shows that the good representation of recycling in CMIP6 models over the Congo (Figure 3d) is partly attributable to compensating errors in underlying model processes.

To understand why CMIP6 models tend to overestimate incoming winds over both study regions, we analyzed associations between basin incoming wind speed and land-surface temperature biases. Wind biases relative to ERA5 are positively correlated with surface temperature biases over each basin ($r = 0.52$, and $r = 0.62$, $p < 0.001$, for Amazon and Congo, respectively, Figure S7 in Supporting Information S1). Positive biases in CMIP6 winds have previously been reported over parts of Africa (Akinsanola et al., 2021), while CMIP6 models underestimate wind speed over the tropical Atlantic (Richter & Tokinaga, 2020). Our analysis of CMIP6 winds focussed on the strength of winds entering the Amazon and Congo, though we might expect differences between conditions over the land and ocean to have some influence over wind biases (Richter et al., 2012). These results suggest why CMIP6 models tend to overestimate moisture advection to the Amazon, illustrating how biases in one variable can result in further biases elsewhere in the climate system.

Comparing results from different versions of the same model or between closely-related models can indicate the effect of model development or resolution increases on model performance. Improvements in model representation of precipitation recycling are more noticeable over the Amazon, as in the Congo most models perform well (Table S7 in Supporting Information S1). In the Amazon, increases in model resolution improved representation of seasonal recycling in four CMIP6 models (CNRM-CM6-1, HadGEM3-GC31, MPI-ESM1-2, NorESM2). Some modeling centers provided multiple model versions, allowing comparisons between models of differing complexity. There are two instances of Earth System models (ESMs), which explicitly represent biogeochemical cycling (Flato, 2011), showing better representation of recycling than the coupled model from the same modeling center (ACCESS-ESM1-5, MIROC-ES2L), and one instance where the ESM performs less well than the equivalent coupled model at the same resolution (CNRM-ESM2-1).

Finally, we analyzed future trends in precipitation recycling over the Amazon and Congo in model simulations from four future climate scenarios (Figure 4). By 2100, recycling is robustly projected to decline over both basins relative to the 1979–2014 baseline, with stronger declines under higher warming scenarios. Reductions in ρ are larger over the Amazon than in the Congo (relative changes of -17.5% and -12.0% by 2100 under the SSP585 scenario, Figures 4a and 4b). The decline in ρ is primarily caused by large increases in imported moisture over both basins (Figures 4e and 4f), while the changes in E are more modest and vary between scenarios (Figures 4c and 4d), likely affected by a combination of land-use change and atmospheric carbon dioxide concentrations (Lawrence et al., 2016). The increase in horizontal moisture transport over the course of the century is consistent with the amplification of the global water cycle in a warming climate (Held & Soden, 2006; Skliris et al., 2016) and was previously observed in the CMIP5 models (Lavers et al., 2015). As moisture transport increases, the land-surface contribution to precipitation is increasingly outweighed by advected moisture.

Our results have implications for projected impacts of deforestation on regional precipitation, as the climate impacts of Amazon land-use change could be underrepresented in CMIP6 models. Figure 4 suggests that climate sensitivity to the land surface may decline in the future. However, it should be noted that due to the "fast recycling" of moisture in the lower boundary layer over the Amazon and Congo basins (Lettau et al., 1979; Pokam

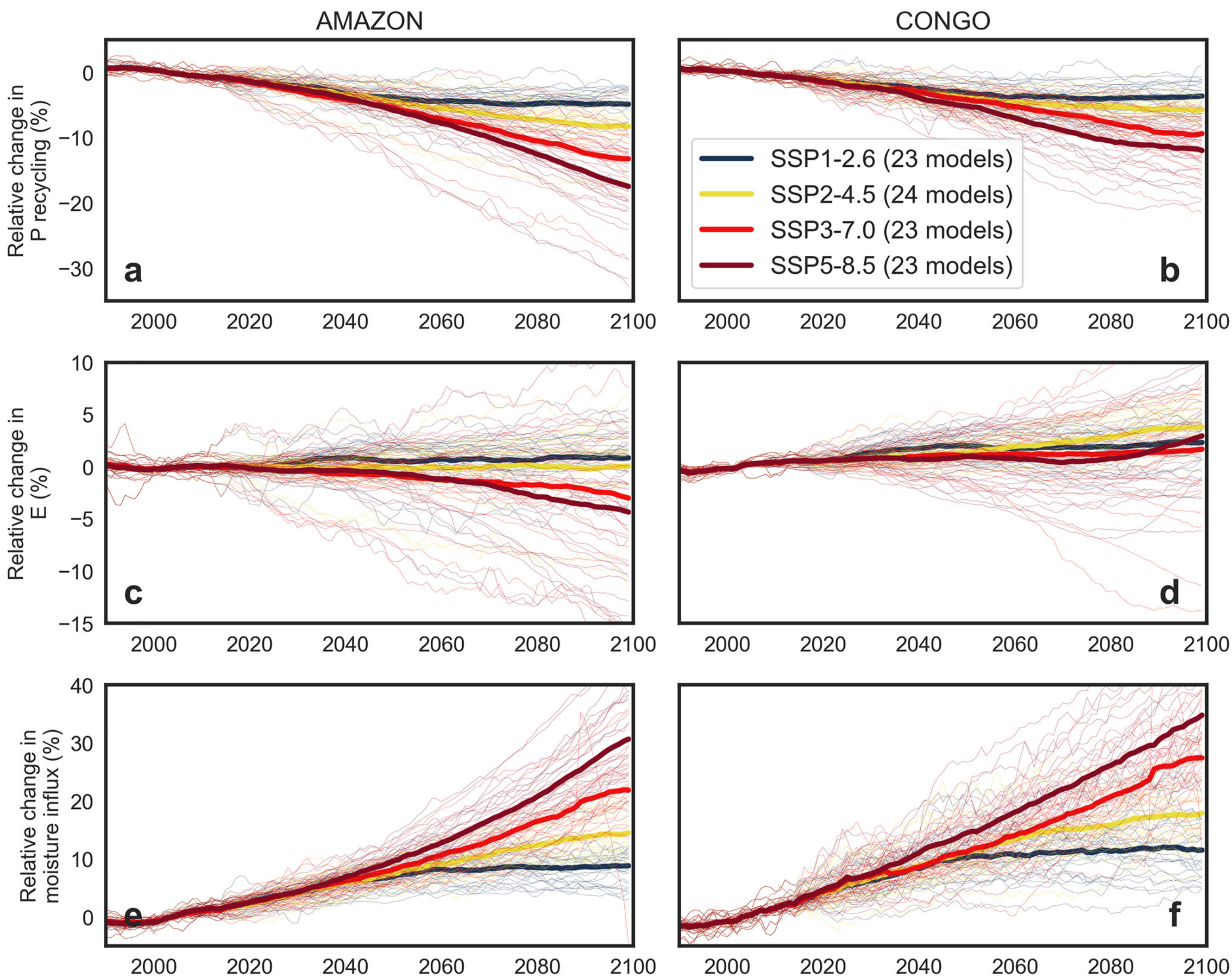

Figure 4. (a and b) Future changes in precipitation (P) recycling calculated using EB94; (c and d) evapotranspiration (E); and (e and f) moisture influx, over the Amazon and Congo basins from four shared socio-economic pathway (SSP) scenarios, calculated relative to the 1979–2014 climatological mean. An 11-year moving average was applied to reduce noise. Each narrow line represents an individual model, and the thick lines show the ensemble means for each SSP.

et al., 2012), future reductions in precipitation recycling caused by increasing moisture transport may not be as extreme as models suggest. Future work evaluating the sources of moisture for precipitation in the presence of incomplete vertical mixing, and assessing how this is represented in climate models would shed further light on the validity of future climate projections.

Data Availability Statement

The Coupled Model Intercomparison Project Phase 6 data set is available at https://esgf-node.llnl.gov/projects/cmip6. ERA5 data are available at https://doi.org/10.24381/cds.6860a573 and https://doi.org/10.24381/cds.f17050d7. JRA-55 data are available at https://doi.org/10.5065/D60G3H5B. MERRA-2 data are available at https://doi.org/10.5067/5ESKGQTZG7FO, https://doi.org/10.5067/0JRLVL8YV2Y4 and https://doi.org/10.5067/V92O8XZ30XBI. CFSR data are available at https://doi.org/10.1175/2010BAMS3001.1. Python scripts to estimate recycling following the EB94 method and the Brubaker method are available in an online repository: https://doi.org/10.5281/zenodo.6511636.

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