AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

Key Points:
- The three major rainforests respond differently to CO_2-induced plant physiology changes
- These differences lie in how the related land-surface warming interacts with the circulation
- They are not driven by differences in evapotranspiration and recycling rate

Correspondence to:
Wenyuan Fan,
marion.saint-lu@lmd.jussieu.fr

Surface Warming and Atmospheric Circulation Dominate Rainfall Changes Over Tropical Rainforests Under Global Warming

Marion Saint-Lu[1] (ID), **Robin Chadwick[2]** (ID), **F. Hugo Lambert[1]**, and **Matthew Collins[1]** (ID)

[1]College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK, [2]Global Systems Institute, University of Exeter, Exeter, UK

Abstract This study investigates how the direct effects of CO_2 quadrupling on plant physiology impact precipitation in three main rainforests. We show that differences between the regions lie in how land-surface warming (driven by reduced transpiration) interacts with their climatological atmospheric circulations, regardless of their reliance on evapotranspiration. Various atmosphere-only experiments from two General Circulation Models are used. We find that over New Guinea, land-surface warming amplifies moisture convergence from the ocean and increases rainfall. In the Congo, no clear rainfall changes emerge as the land-surface warming effect is offset by migrations of rainfall. In Amazonia, the interaction of land-surface warming with the climatological circulation pattern leads to a precipitation-change dipole, with reduced rainfall in central and eastern Amazonia and increased rainfall in the west.

Plain Language Summary Predicting how tropical rainforests will be influenced by climate change is crucial and remains a challenge. We show that precipitation changes over rainforests are predominantly driven by land-surface warming, caused by reduced transpiration from plants and its interaction with the atmospheric circulation in each region, which explains why each rainforest responds differently. These results rely on model experiments that decompose the complex effects of vegetation changes caused by rising CO_2. This study points towards two main ways of reducing uncertainties in future projections: 1) by improving the models' representation of tropical circulation and vegetation and 2) by searching for emergent constraints on rainforest atmospheric circulation and the impact of vegetation changes.

1. Introduction

Rainforests rely on precipitation to survive. They are a sanctuary for wildlife (Myers, 1988) and hold substantial amounts of carbon (Saatchi et al., 2011). Rising CO_2 is expected to reduce precipitation over most of Amazonia, the biggest rainforest on Earth (Boisier et al., 2015; Chadwick et al., 2016, 2017; Fasullo, 2012; Joetzjer et al., 2013; Lambert et al., 2017). The most extreme projections of rainfall change could cause Amazon dieback (Cox et al., 2004), with a risk of extinction for many forest species, along with carbon releases amplifying the effects of climate change at the global scale. These risks add to the effects of deforestation. Understanding how tropical forest precipitation responds to rising CO_2 is necessary for adaptation policy to sustain rainforests.

Rising CO_2 drives contrasting rainfall changes over Amazonia, the Congo basin, and the Maritime Continent, which are not yet fully understood (Kooperman et al., 2018). For an abrupt quadrupling of atmospheric CO_2 (abrupt4xCO2), the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012) multimodel mean shows that Amazonia is projected to experience drying in most General Circulation Models (GCMs), although with substantial intermodel disagreement (Figure 1). However, there is strong model agreement over New Guinea for an intensification of rainfall. Over some parts of the Congo basin, a slight rainfall increase is expected with good model agreement, but no clear rainfall change is detected over the rest of the region.

Rising CO_2 weakens plant transpiration by reducing stomatal conductance (Cox et al., 1999; Dong et al., 2009; Pu & Dickinson, 2014; Sellers et al., 1996). It also increases the Leaf Area Index by boosting CO_2 fertilization. The net effect of plant physiological changes appears to reduce transpiration, at least in models. This plant effect, as we will refer to it, is a major driver of rainfall changes over tropical rainforests
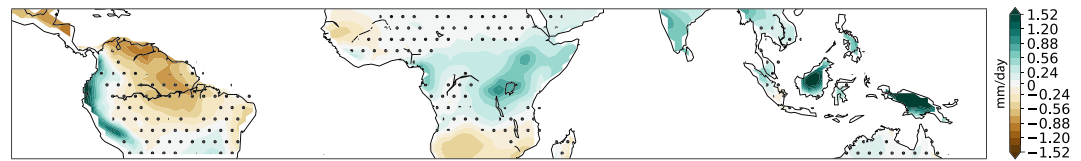
Figure 1. Annual mean precipitation change over tropical land in abrupt4xCO2 given by the Coupled Model Intercomparison Project Phase 5 multimodel mean. Dots show where less than 20 models out of 29 agree on the sign of change given by the multimodel mean. The 29 models are listed in Table S1.

(Betts et al., 2004; Cao et al., 2012; Chadwick et al., 2017; Kooperman et al., 2018; Richardson et al., 2018). Since transpiration is a major contributor to evapotranspiration (ET) over rainforests (Kumagai et al., 2005; Pu & Dickinson, 2014), the plant effect reduces ET, which tends to reduce precipitation (effect of reduced ET). On the other hand, reduced transpiration warms the land surface by reducing its cooling capacity, which drives anomalous sensible heating, wind, and moisture convergence and tends to increase rainfall (effect of land-surface warming). Both the effect of reduced ET and the effect of land-surface warming come from the same physical process, that is, reduced transpiration, but have different consequences through different processes.

Previous modeling studies have hypothesized that the difference between Amazonia and New Guinea rainfall responses to rising CO_2 lies in their different present-day reliance on ET (strong recycling over Amazonia, weak over New Guinea) and proximity to the ocean (Chadwick et al., 2019; Kooperman et al., 2018). The idea of this hypothesis, that we will refer to as the recycling hypothesis, is that when rainfall relies strongly on local ET, it is more sensitive to reduced ET than to land-surface warming. No strong evidence has been provided yet to support it.

Here we first use an atmosphere-only GCM experiment performed with HadGEM2-ES (Martin et al., 2011) that shows the plant effect induced by an abrupt quadrupling of atmospheric CO_2 (rising CO_2 is only seen by vegetation, not by radiation), where sea surface temperatures are prescribed to pre-industrial conditions and land temperatures are free to vary (PHYS; Chadwick et al., 2017). We also use PHYSb, which is the same as PHYS but performed with ACCESS1.0 (Ackerley & Dommenget, 2016; Bi et al., 2013) and with sea surface temperatures prescribed to observations. ACCESS1.0 and HadGEM2-ES are very similar models sharing the same configurations of their atmospheric and land-surface components. We then use "prescribed land" atmosphere-only GCM experiments performed with ACCESS1.0, where the surface temperature over land is prescribed, so that the effects of reduced ET and land-surface warming, both induced by the plant effect, can be separated (Ackerley & Dommenget, 2016; Ackerley et al., 2018; Chadwick et al., 2019). These experiments are referred to as PHYS-evap (land is not allowed to warm, plant physiological changes only affect ET) and PHYS-warming (land is prescribed to warm as when fully responding to plant physiological changes, but the plant physiology does not change). Boundary conditions and model choices are detailed in supporting information, Text S2 and Tables S2 and S3. In this study, we analyze circulation and moisture budgets in these experiments in order to test the recycling hypothesis and further understand the rainfall response to rising CO_2 over rainforests.

2. New Guinea

Figure 2a shows that the pre-industrial (piControl) annual mean rainfall rate is strong over New Guinea (about 9 mm/day in the HadGEM2-ES piControl experiment). It results from a high occurrence of deep convection, shown by the mean wind convergence into the region at mid and low levels and divergence at around 200 hPa (Figure 2k). Moisture convergence and ET each account for about half of the moisture supply for precipitation (Figure 2a).

The PHYS rainfall change dominates the full abrupt4xCO2 response and is consistent with the CMIP5 mean (Figures 1, S1a, S1c). It consists in increasing rainfall over New Guinea (Figures 2f and S1c). This rainfall increase is largely attributable to increased column-integrated moisture convergence onto the island, driven by low-level wind changes rather than by moisture changes (Figure 2f).

Figure 3 shows that the PHYS rainfall increase is reproduced by PHYSb and that it results from the effect of land-surface warming (PHYS-warming). Land-surface warming drives anomalous low-level wind convergence onto the island and amplifies moisture convergence from the ocean. This is consistent with the
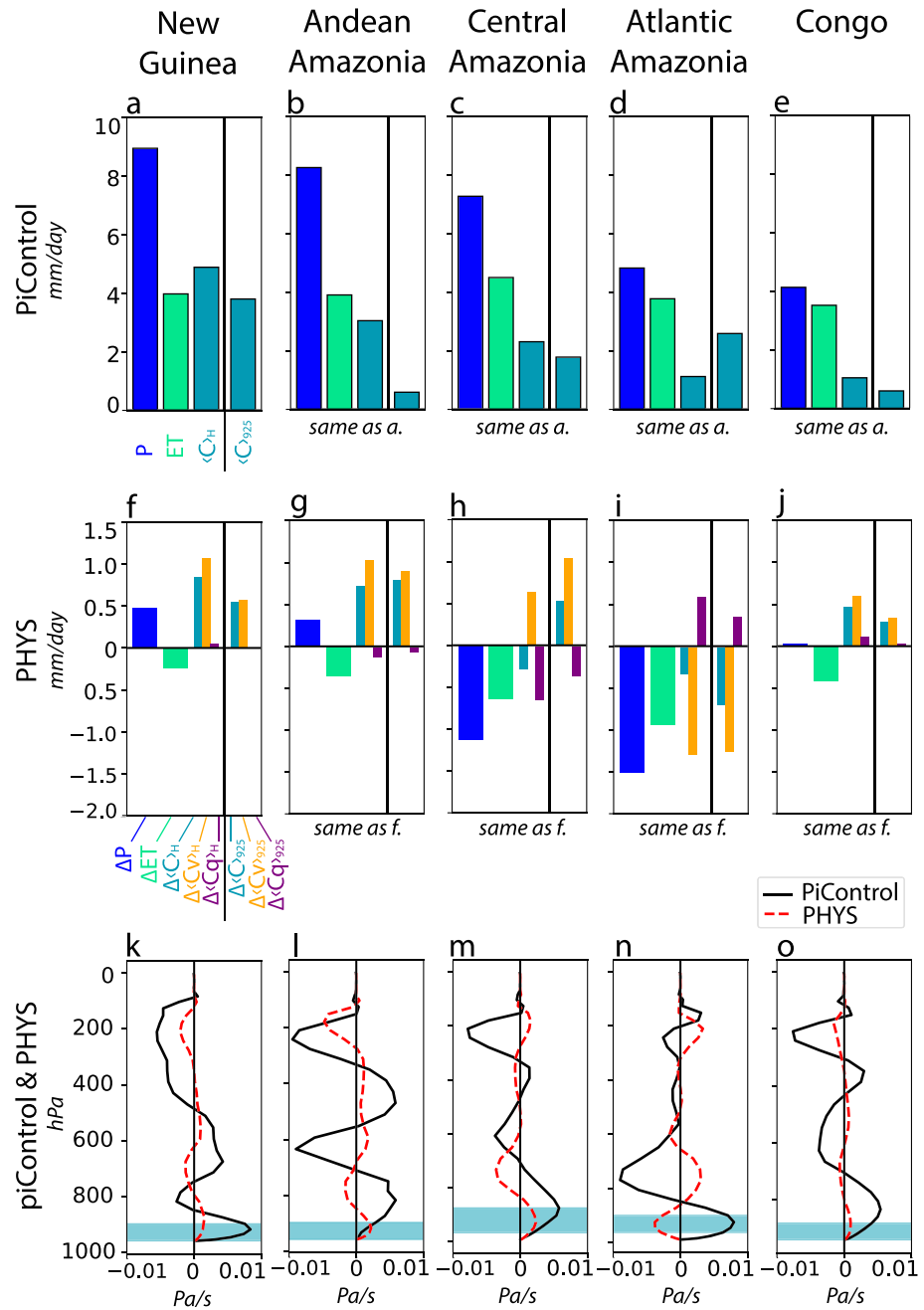
Figure 2. Top line: piControl (HadGEM2-ES) annual mean moisture budget for each region shown in Figure 3, showing precipitation (P), evapotranspiration (ET), moisture convergence over the whole column $< C >_H$ and moisture convergence over low levels $< C >_{925}$. The vertical line separates the whole column moisture budget from the low-level moisture convergence. Middle line: PHYS annual mean changes in the moisture budget for each region, showing changes in precipitation ΔP, in evapotranspiration ΔET, in the whole-column moisture convergence $\Delta < C >_H$, in the low-level moisture convergence $\Delta < C >_{925}$, and in their dynamical and thermodynamical components $\Delta < Cv >_h$ and $\Delta < Cq >_h$ (h being either H or 925), which separate moisture convergence changes due to changes in winds and specific humidity, respectively. Bottom line: annual mean vertical profiles of horizontal wind convergence in each region, in piControl (black line) and its change in PHYS (PHYS - piControl; dashed red line). The layer shaded in blue is the layer over which low-level moisture convergence is integrated. See supporting information, Text S1 for mathematical definitions.
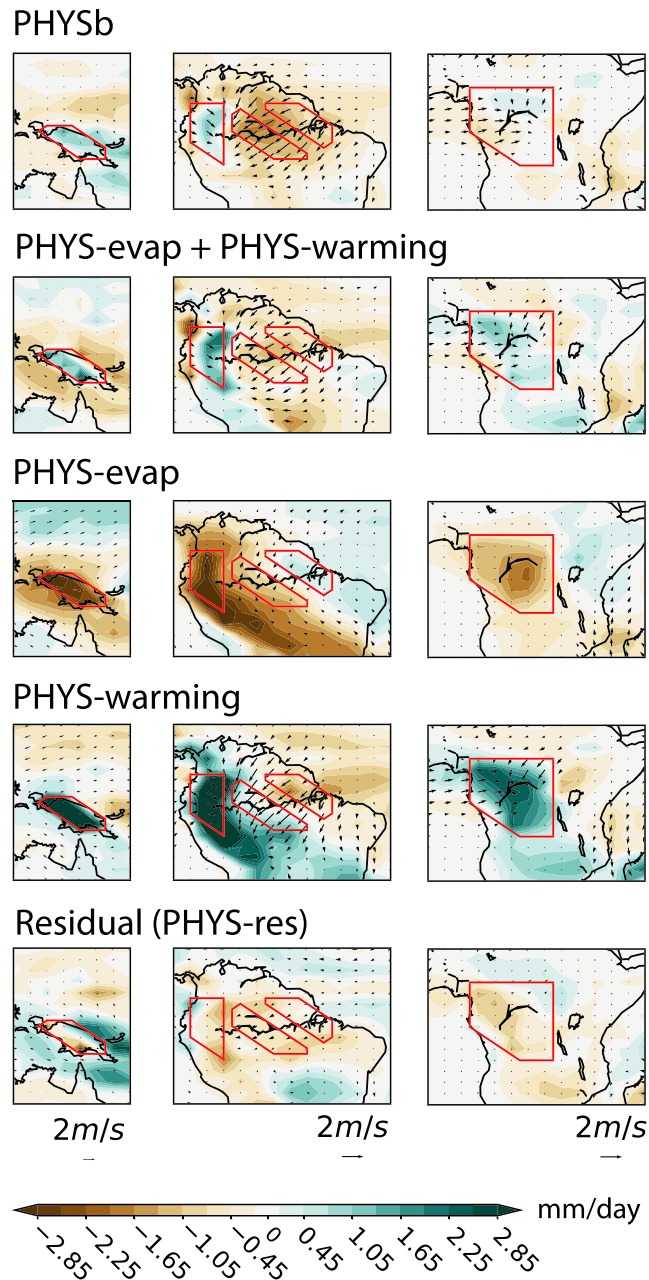
Figure 3. Changes in annual mean precipitation (colors) and horizontal wind at 925 hPa (vector field) over all regions, in response to the different components of the plant effect (as given by the ACCESS1.0 prescribed land experiments). PHYSb: plant effect; PHYS-evap: effect of reduced evapotranspiration: PHYS-warming: effect of land-surface warming; PHYS-res = PHYSb - (PHYS-evap + PHYS-warming). Red contours show the different regions defined and used in this study.

increase in low-level wind convergence, in moisture convergence, and in rainfall caused by the plant effect (Figures 2f and 2k; low levels are indicated by the blue shading in Figure 2k).

3. Amazonia

We divide Amazonia into three regions that have different rainfall responses in each experiment: Andean, central Amazonia, and Atlantic Amazonia (shown in Figure 3). The Amazon's present-day circulation is characterized in the annual mean by northeasterly winds from the Atlantic (Figure S2) associated with stronger horizontal moisture convergence and about double the precipitation in Andean compared with Atlantic Amazonia (Figures 2b and 2d). Andean Amazonia is similar to New Guinea, with a high occurrence
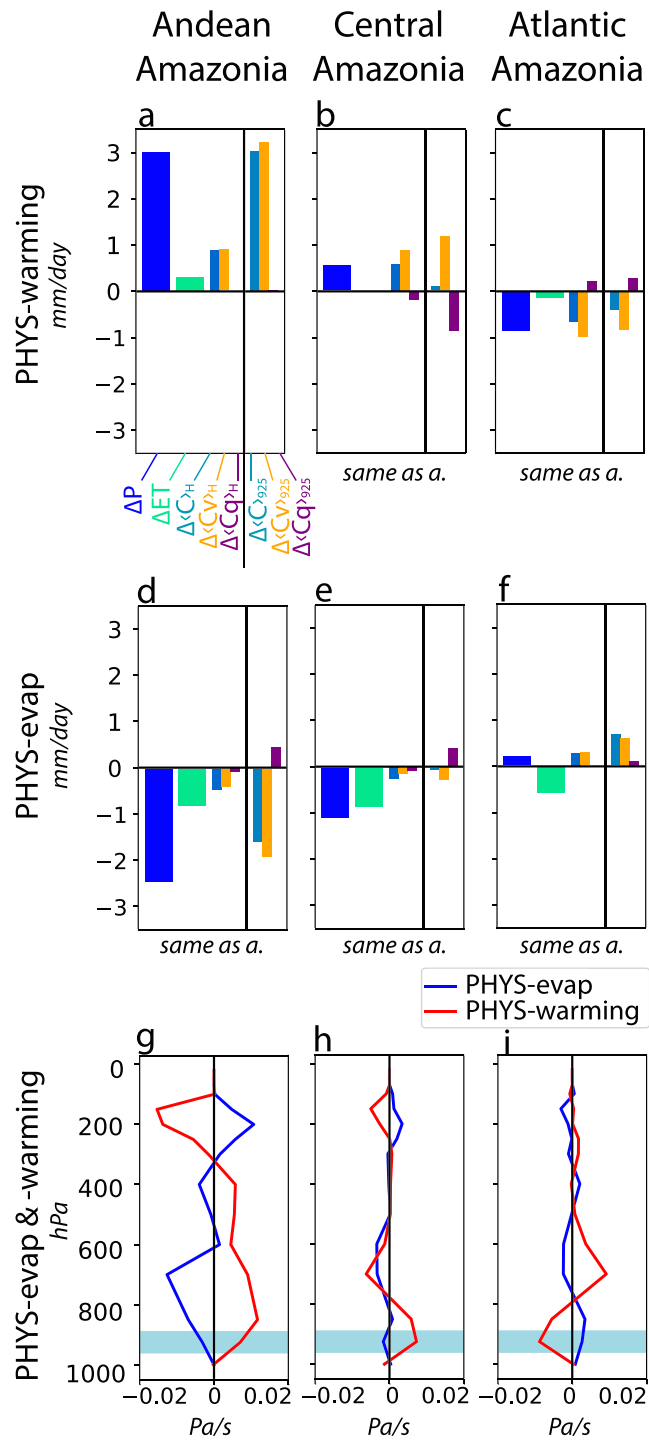
Figure 4. Top line: same as middle line of Figure 2 but for PHYS-warming changes and only over Amazonia regions. Middle line: same for PHYS-evap changes. Bottom line: same as bottom line of Figure 2 but showing PHYS-evap change (blue line) and PHYS-warming change (red line) and only over Amazonia regions.

of deep convection and moisture convergence and ET each accounting for about half of the moisture supply for precipitation (Figures 2b and 2l). Central Amazonia similarly exhibits a high occurrence of deep convection, high precipitation, and strong moisture supply from horizontal convergence (Figures 2c and 2m). Over Atlantic Amazonia, the dominant circulation regime is shallow convection with wind convergence at the surface and divergence just above the boundary layer (Figure 2n). Deep convection is very active during the transition and wet seasons, but the dry season is longer there than in Andean and central Amazonia (Machado et al., 2004). This region exhibits strong recycling between ET and precipitation (Figure 2d).

The PHYS-evap and PHYS-warming rainfall responses have the same dipole pattern with opposite signs (Figure 3). A striking result is that reduced ET (PHYS-evap) actually increases rainfall in eastern Amazonia. The effect of land-surface warming, instead, is responsible for drying that region. This does not support the recycling hypothesis, since Atlantic Amazonia has the strongest reliance on ET, yet a reduction in the latter actually increases rainfall there. Both effects are investigated in the following.

Why does land-surface warming dry Atlantic Amazonia? In order to test whether this pattern is associated with the pattern of the land warming forcing, we use another prescribed land experiment where all land is uniformly warmed by 4 K (LAND4K; see Tables S2 and S3). Figure S3 shows that the rainfall response to uniformly warmed land exhibits a similar pattern as PHYS-warming. Since the emergence of this dipole is not related to the pattern of the forcing or its nature (same dipole in PHYS-warming and PHYS-evap), it is likely to be related to the climatological wind field and spatial pattern of convection.

Land-surface warming (PHYS-warming) increases low and midlevel wind convergence in Andean Amazonia, where it is already strong in the climatology (Figures 4a and 4g). It increases moisture convergence and thus precipitation in Andean Amazonia (Figure 4a). It seems that precipitation increases the most where deep convection is the dominant regime, over Andean Amazonia. By mass conservation, it has to lead to anomalous wind and moisture divergence somewhere else, which the model shows is over Atlantic Amazonia, reducing precipitation there (Figures 4c and 4i). A vertical cross-section of the circulation change reveals that an anomalous overturning circulation takes place within the low troposphere (up to 500 hPa) between Andean and Atlantic Amazonia (Figure S4). These elements suggest that the PHYS-warming response over Atlantic Amazonia, consisting in anomalous subsidence and reduced rainfall, originates from low levels, probably driven by anomalous moisture convergence and shallow convective outflow over the Andes.

Why does reduced ET moisten Atlantic Amazonia? In PHYS-evap, ET is similarly reduced in all three regions, but more strongly affects deep convection in Andean Amazonia where it is stronger in the climatology (Figures 4d, 4e, and 4f). In this region, reduced ET drives precipitation decreases, reducing the latent heat release in the atmosphere, which creates anomalous wind divergence in the low and midlevels (Figures 4d and 4g). Here the wind convergence response is maximum at around 700 hPa, while the wind convergence response to PHYS-warming is maximum at around 850 hPa (Figure 4g). This contrast in the height of wind responses suggests that reduced ET directly decreases atmospheric heating by decreasing precipitation, which then affects wind convergence, while land-surface warming directly affects wind convergence by reducing the local boundary layer pressure through sensible heating. Anomalous wind divergence over Andean Amazonia drives anomalous wind and moisture convergence over Atlantic Amazonia (Figures 4f and 4i). A vertical cross-section reveals again an anomalous circulation taking place within the low troposphere between Andean and Atlantic Amazonia (Figure S4). Here again, these elements suggest that the PHYS-evap response over Atlantic Amazonia is forced at low levels. The competition between anomalous moisture convergence and locally reduced ET results in a slight increase in precipitation over that region (Figure 4f); as noted before, the effect of reduced ET actually increases precipitation over eastern Amazonia. Over central Amazonia, the PHYS-evap response exhibits no substantial net change in moisture convergence, so that precipitation decreases in association with reduced ET (Figure 4e).

The residual component is comparatively small, but not negligible (PHYS-res, Figure 3). It consists in a reduction of rainfall over all three regions and results from interactions between the effects of land-surface warming and reduced ET. For example, reduced ET could reduce the cloud cover, which would be captured in PHYS-evap but not in PHYS-warming (even though it would contribute to the prescribed land-surface warming). Thus, rainfall could increase too much in PHYS-warming, and in the sum of PHYS-warming and PHYS-evap, compared to the coupled PHYSb. Another possible interaction is the convergence of drier air due to reduced ET, into the area of convection, intensified by land-surface warming on the western half of Amazonia. This nonlinearity might be enhanced or made possible by the fact that the effects of reduced ET and

land-surface warming have slightly different spatial extensions: The region of rainfall decrease in response to PHYS-evap is more extended spatially than the region of rainfall increase in response to PHYS-warming (Figure 3). As a consequence, when combining the two effects, the air converging into the region of intensified convection and coming from its margins is drier because of reduced ET, which dominates on the margins. Indeed, PHYS-res decreases rainfall over all rainforest regions, with similar magnitudes (Figure 3).

Despite PHYS-res, the rainfall response to the net plant effect (PHYSb/PHYS) is very similar to the sum of PHYS-evap and PHYS-warming (Figure 3). Central and Atlantic Amazonia experience less rainfall while Andean Amazonia experiences more rainfall (Figures 2g, 2h, 2i, and 3). This dipole response is mainly dominated by the effect of land-surface warming, with the exception of central Amazonia. As detailed above, land-surface warming drives rainfall increases in Andean Amazonia, where climatological deep convection and moisture convergence are strong, and subsequently drives rainfall decreases in Atlantic Amazonia. Consistent with this, part of the PHYS rainfall reduction in Atlantic Amazonia is attributable to reduced column-integrated moisture convergence due to reduced low-level wind convergence (Figure 2i). The biggest part is associated with reduced ET, but a large part of the ET reduction itself could be due to reduced rainfall. A decrease in runoff might be also expected since precipitation decreases more than ET, although this could be offset by the increasing intensity of rainfall events under plant physiological forcing (Skinner et al., 2017). Central Amazonia, since it is in between those two regions, does not experience any notable change in moisture convergence, so precipitation is reduced because of both reduced ET and residual nonlinearities.

This ascent-descent dipole is a robust response to the plant effect across CMIP5 (Kooperman et al., 2018; Richardson et al., 2018). Previous studies suggested that it is mostly driven by reduced ET, which would reduce rainfall where it strongly relies on ET, that is, over eastern Amazonia, and enhances the transport of moisture from the Atlantic to the Andes, increasing rainfall over there (Kooperman et al., 2018; Langenbrunner et al., 2019). According to this hypothesis, eastern Amazonia dries first in response to the plant effect because of a drier and warmer boundary layer suppressing convection, leading to moisture building up on top of the boundary layer, ultimately increasing rainfall over the Andes, as this moisture is advected westward (Langenbrunner et al., 2019). However, separating the effects of land-surface warming and reduced ET reveals that the dipole is instead primarily caused by land-surface warming and fundamentally driven by the response over Andean Amazonia rather than over the eastern lowlands. Comparison with a uniform land warming experiment confirms that this dipole does not emerge from the pattern of the forcing, or its nature. We thus suggest an alternative view, where this dipole emerges from the Amazon circulation and spatial pattern of convection: Land-surface warming increases low-level moisture and wind convergence where it is stronger in the climatology, over western Amazonia on the Andes slopes. By mass conservation, it drives anomalous moisture divergence on the other side of Amazonia, closer to the Atlantic.

4. Congo

Over the Congo basin (region shown in Figure 3), the climatological regime consists in moderate rainfall with strong reliance on ET and frequent occurrence of deep convection, as shown by the wind divergence at around 200 hPa (Figure 2e,o). The effect of land-surface warming slightly dominates the effect of reduced ET, so that the sum of PHYS-evap and PHYS-warming results in rainfall increases over this region (Figure 3).

The net plant effect (PHYS/PHYSb) results in no substantial rainfall change over the Congo basin (Figures 2j and 3), meaning that the residual component offsets the rainfall increase that results from the combination of the effects of land-surface warming and reduced ET (Figure 3). PHYS-evap and PHYS-warming rainfall responses both appear weaker over the Congo basin than over western Amazonia or New Guinea, which could explain why their addition is more easily offset by nonlinearities (Figure 3). Strong migrations of rainfall associated with the monsoon could cause PHYS-evap and PHYS-warming responses to be weaker over the Congo basin in the annual mean than over other regions. Indeed, for a few months, it rains either in the northern or in the southern half of the region (Figure S5), which weakens the response in each grid point in annual mean. This is not the case over western Amazonia or New Guinea, where the rainfall response to PHYS-evap or PHYS-warming is nearly homogeneous over the whole region throughout the year (Figures S6 and S7).

5. Difference Between the Three Rainforests

When comparing abrupt4xCO2 precipitation and ET changes over central/eastern Amazonia across CMIP5 models, a very strong relationship emerges (Figure S8a). This could lead to the conclusion that

precipitation responds very strongly to reduced ET in this region and to conclude that this is due to its strong present-day reliance on ET. However, no relationship emerges over the Congo basin despite its strong recycling rate (Figure S8b). Amazonia is the only rainforest region of the three where rainfall is expected to broadly decrease in a majority of models. This is very likely to be the reason why the precipitation change is so well correlated with the ET change in this region, since ET is reduced as a consequence of both the plant effect and reduced precipitation itself. Over the Congo basin and New Guinea the majority of models project an increase in rainfall, which tends to increase ET, competing with the reduction initially induced by the plant effect and resulting in no correlation between precipitation and ET changes.

Separating the effects of reduced ET and land-surface warming reveals that the projected rainfall reduction over eastern Amazonia is not driven by reduced transpiration directly, as could have been expected from the strong recycling over this region and the strong relationship with reduced ET across CMIP5 models. More generally for the three rainforests, we show that a strong recycling of precipitation with ET does not imply a stronger sensitivity of precipitation to ET changes. Besides, a decrease in local ET does not necessarily imply a decrease in precipitation, even in regions with strong recycling.

According to our findings, the reason why the Amazon, the Congo, and New Guinean tropical rainforests are not affected the same way by plant physiological changes is their difference in climatological circulation and convective regime. New Guinea constitutes a localized region of deep convection and moisture convergence. The effect of land-surface warming induced by plants, which, to first order, is stronger than the effect of reduced ET over all three rainforests, directly leads to a rainfall increase over the whole island. On the contrary, the Amazon forest is subject to a strong climatological circulation pattern (Figure S2). Land-surface warming increases rainfall over western Amazonia, where climatological low-level winds converge and deep convection is frequent, and dries eastern Amazonia, where low-level winds are southwestward and deep convection is less frequent. Over central Amazonia, reduced ET is left to dominate the rainfall response, since this region stands in the middle of the anomalous ascent-descent dipole. Nonlinear interactions between the two effects further reduce rainfall there. Finally, the Congo forest is subject to strong migrations of rainfall throughout the year, which weakens the dominant effect of land-surface warming and induces more nonlinearities, resulting in no clear rainfall change.

Note that moisture convergence increases over western Amazonia as much as over New Guinea in response to the plant effect (Figures 2g and 2f). Therefore, the strong rainfall increase over New Guinea, in contrast with the rainfall decrease over Amazonia, is not attributable to a presumably better moisture availability due to the fact that it is an island, since moisture is no less available over Amazonia.

The complexity of the rainforest precipitation changes, and their dependencies on climatological circulation may explain the substantial model disagreement over Amazonia and the Congo basin in response to rising CO_2. It is also consistent with the good agreement over New Guinea, since the circulation and spatial pattern of convection are strongly constrained by the island, which does not move from one model to another. Another reason for model disagreement is that models do not all simulate the plant effect. Figure S9 shows that the rainfall response to abrupt4xCO2 is slightly stronger, over tropical land, when only the models that simulate the plant effect are averaged, and most importantly that model agreement is improved.

6. Conclusion

How tropical rainforests will respond to CO_2-driven plant physiological changes will impact the Earth's biodiversity and carbon emissions. Our results show that the Amazon, the Congo, and New Guinean rainforests are not affected the same way by plant physiological changes because of their different climatological circulation patterns. Climatological recycling ratios between precipitation and ET, on the other hand, do not affect how sensitive the forest is to reduced ET. The effect of land-surface warming induced by plants is stronger than the effect of reduced ET, to first order, over the three rainforests, regardless of their recycling ratios. It directly increases rainfall over New Guinea, which is a localized convergence region. Over Amazonia, the combination of this effect with strong climatological winds creates a precipitation change dipole, driven by the response over Andean Amazonia and characterized by the drying of central and eastern Amazonia. Over the Congo forest, rainfall changes are uncertain, possibly because of interactions with the African monsoon.

This work highlights the importance of the representation of the plant effect in future model versions. Our results rely on two models, of which the patterns of abrupt4xCO2, PHYS and PHYSb precipitation change,

are representative of the CMIP5 ensemble (compare Figure 1 with Figure S1). HadGEM2-ES, in particular, realistically captures the climatological Amazonian rainfall (Yin et al., 2013). It is worth keeping in mind that our results might be model dependent and that we cannot exclude the possibility, albeit small, that the rainfall response from PHYS, although consistent with PHYSb, results from different mechanisms. Replicating the PHYS-evap and PHYS-warming experiments with other models, as well as using finer vertical and horizontal resolutions, could help to further understand the mechanisms that drive rainfall changes over rainforests.

This work points towards two approaches for reducing uncertainty in these key tropical regions of Earth. The first involves improving the representation of the tropical circulation and moisture convergence, coupled with improved parametrization of the land-surface effects of plant physiology. The second involves model selection and a search for emergent constraints to narrow multimodel ranges (Collins et al., 2012). The identification of the importance of the atmospheric circulation and the impact of both plant effects should guide that search. These would result in more robust projections of the future with reduced uncertainties that can improve decision-making and adaptation policy related to rainfall shifts in the tropics.

References

Ackerley, D., Chadwick, R., Dommenget, D., & Petrelli, P. (2018). An ensemble of AMIP simulations with prescribed land surface temperatures. *Geoscientific Model Development*, *11*(9), 3865–3881. https://doi.org/10.5194/gmd-11-3865-2018

Ackerley, D., & Dommenget, D. (2016). Atmosphere-only GCM (ACCESS1.0) simulations with prescribed land surface temperatures. *Geoscientific Model Development*, *9*(6), 2077–2098. https://doi.org/10.5194/gmd-9-2077-2016

Betts, R. A., Cox, P. M., Collins, M., Harris, P. P., Huntingford, C., & Jones, C. D. (2004). The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming. *Theoretical and Applied Climatology*, *78*(1), 157–175. https://doi.org/10.1007/s00704-004-0050-y

Bi, D., Dix, M., Marsland, S., O'Farrell, S., Rashid, H., Uotila, P., et al. (2013). The ACCESS coupled model: Description, control climate and evaluation. *Australian Meteorological and Oceanographic Journal*, *63*, 41–64 en-AU. https://doi.org/10.22499/2.6301.004

Boisier, J. P., Ciais, P., Ducharne, A., & Guimberteau, M. (2015). Projected strengthening of Amazonian dry season by constrained climate model simulations. *Nature Climate Change*, *5*(7), 656–660. https://doi.org/10.1038/nclimate2658

Cao, L., Bala, G., & Caldeira, K. (2012). Climate response to changes in atmospheric carbon dioxide and solar irradiance on the time scale of days to weeks. *Environmental Research Letters*, *7*(3), 034015. https://doi.org/10.1088/1748-9326/7/3/034015

Chadwick, R. (2016). Which aspects of CO2 forcing and SST warming cause most uncertainty in projections of tropical rainfall change over land and ocean? *Journal of Climate*, *29*(7), 2493–2509. https://doi.org/10.1175/JCLI-D-15-0777.1

Chadwick, R., Ackerley, D., Ogura, T., & Dommenget, D. (2019). Separating the influences of land warming, the direct CO2 effect, the plant physiological effect and SST warming on regional precipitation changes. *Journal of Geophysical Research: Atmospheres*, *124*, 624–640. https://doi.org/10.1029/2018JD029423

Chadwick, R., Douville, H., & Skinner, C. B. (2017). Timeslice experiments for understanding regional climate projections: Applications to the tropical hydrological cycle and European winter circulation. *Climate Dynamics*, *49*, 1–19. https://doi.org/10.1007/s00382-016-3488-6

Chadwick, R., Good, P., & Willett, K. (2016). A simple moisture advection model of specific humidity change over land in response to SST warming. *Journal of Climate*, *29*(21), 7613–7632. https://doi.org/10.1175/JCLI-D-16-0241.1

Collins, M., Chandler, R. E., Cox, P. M., Huthnance, J. M., Rougier, J., & Stephenson, D. B. (2012). Quantifying future climate change. *Nature Climate Change*, *2*(6), 403–409. https://doi.org/10.1038/nclimate1414

Cox, P. M., Betts, R. A., Bunton, C. B., Essery, R. L. H., Rowntree, P. R., & Smith, J. (1999). The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Climate Dynamics*, *15*(3), 183–203. https://doi.org/10.1007/s003820050276

Cox, P. M., Betts, R. A., Collins, M., Harris, P. P., Huntingford, C., & Jones, C. D. (2004). Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theoretical and Applied Climatology*, *78*(1), 137–156. https://doi.org/10.1007/s00704-004-0049-4

Dong, B., Gregory, J. M., & Sutton, R. T. (2009). Understanding land-sea warming contrast in response to increasing greenhouse gases. Part I: Transient adjustment. *Journal of Climate*, *22*(11), 3079–3097. https://doi.org/10.1175/2009JCLI2652.1

Fasullo, J. (2012). A mechanism for land-ocean contrasts in global monsoon trends in a warming climate. *Climate Dynamics*, *39*(5), 1137–1147. https://doi.org/10.1007/s00382-011-1270-3

Joetzjer, E., Douville, H., Delire, C., & Ciais, P. (2013). Present-day and future Amazonian precipitation in global climate models: CMIP5 versus CMIP3. *Climate Dynamics*, *41*(11-12), 2921–2936. https://doi.org/10.1007/s00382-012-1644-1

Kooperman, G. J., Chen, Y., Hoffman, F. M., Koven, C. D., Lindsay, K., Pritchard, M. S., et al. (2018). Forest response to rising CO2 drives zonally asymmetric rainfall change over tropical land. *Nature Climate Change*, *8*(5), 434–440. https://doi.org/10.1038/s41558-018-0144-7

Kumagai, T., Saitoh, T. M., Sato, Y., Takahashi, H., Manfroi, O. J., Morooka, T., et al. (2005). Annual water balance and seasonality of evapotranspiration in a Bornean tropical rainforest. *Agricultural and Forest Meteorology*, *128*(1), 81–92. https://doi.org/10.1016/j.agrformet.2004.08.006

Lambert, F. H., Ferraro, A. J., & Chadwick, R. (2017). Land-ocean shifts in tropical precipitation linked to surface temperature and humidity Change. *Journal of Climate*, *30*(12), 4527–4545. https://doi.org/10.1175/JCLI-D-16-0649.1

Langenbrunner, B., Pritchard, M. S., Kooperman, G. J., & Randerson, J. T. (2019). Why does Amazon precipitation decrease when tropical forests respond to increasing CO2? *Earth's Future*, *7*, 450–468. https://doi.org/10.1029/2018EF001026

Lawrence, B. N., Bennett, V. L., Churchill, J., Juckes, M., Kershaw, P., Pascoe, S., et al. (2013). Storing and manipulating environmental big data with JASMIN. In *2013 IEEE International Conference on Big Data*, pp. 68–75. https://doi.org/10.1109/BigData.2013.6691556

Machado, L. A. T., Laurent, H., Dessay, N., & Miranda, I. (2004). Seasonal and diurnal variability of convection over the Amazonia: A comparison of different vegetation types and large scale forcing. *Theoretical and Applied Climatology*, *78*(1), 61–77. https://doi.org/10.1007/s00704-004-0044-9

Martin, G. M., Bellouin, N., Collins, W. J., Culverwell, I. D., Halloran, P. R., Hardiman, S. C., et al. (2011). The HadGEM2 family of Met Office Unified Model climate configurations. *Geoscientific Model Development*, *4*(3), 723–757. https://doi.org/10.5194/gmd-4-723-2011

Myers, N. (1988). Threatened biotas: "Hot spots" in tropical forests. *Environmentalist*, *8*(3), 187–208. https://doi.org/10.1007/BF02240252

Pu, B., & Dickinson, R. E. (2014). Hydrological changes in the climate system from leaf responses to increasing CO2. *Climate Dynamics*, *42*(7-8), 1905–1923. https://doi.org/10.1007/s00382-013-1781-1

Richardson, T. B., Forster, P. M., Andrews, T., Boucher, O., Faluvegi, G., Fläschner, D., et al. (2018). Carbon dioxide physiological forcing dominates projected eastern Amazonian drying. *Geophysical Research Letters*, *45*, 2815–2825. https://doi.org/10.1002/2017GL076520

Rodríguez, J. M., Milton, S. F., & Marzin, C. (2017). The East Asian atmospheric water cycle and monsoon circulation in the Met Office Unified Model. *Journal of Geophysical Research: Atmospheres*, *122*, 10,246–10,265. https://doi.org/10.1002/2016JD025460

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T. A., Salas, W., et al. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences*, *108*(24), 9899–9904. https://doi.org/10.1073/pnas.1019576108

Seager, R., Naik, N., & Vecchi, G. A. (2010). Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming. *Journal of Climate*, *23*(17), 4651–4668. https://doi.org/10.1175/2010JCLI3655.1

Sellers, P. J., Bounoua, L., Collatz, G. J., Randall, D. A., Dazlich, D. A., Los, S. O., et al. (1996). Comparison of radiative and physiological effects of doubled atmospheric CO2 on climate. *Science*, *271*(5254), 1402–1406. https://doi.org/10.1126/science.271.5254.1402

Skinner, C. B., Poulsen, C. J., Chadwick, R., Diffenbaugh, N. S., & Fiorella, R. P. (2017). The role of plant CO2 physiological forcing in shaping future daily-scale precipitation. *Journal of Climate*, *30*(7), 2319–2340. https://doi.org/10.1175/JCLI-D-16-0603.1

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, *93*(4), 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1

Yin, L., Fu, R., Shevliakova, E., & Dickinson, R. E. (2013). How well can CMIP5 simulate precipitation and its controlling processes over tropical South America?. *Climate Dynamics*, *41*(11), 3127–3143. https://doi.org/10.1007/s00382-012-1582-y