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CO_2 fertilization effect can cause rainfall decrease as strong as large-scale deforestation in the Amazon

Gilvan Sampaio[1], Marília Shimizu[1], Carlos A. Guimarães-Júnior[1], Felipe Alexandre[1], Manoel Cardoso[2], Tomas F. Domingues[3], Anja Rammig[4], Celso von Randow[2], Luiz F. C. Rezende[2], David M. Lapola[5]

[1] Centro de Previsão de Tempo e Estudos Climáticos, Instituto Nacional de Pesquisas Espaciais, Cachoeira Paulista SP, 12630-000, Brazil

[2] Centro de Ciência do Sistema Terrestre, Instituto Nacional de Pesquisas Espaciais, São José dos Campos SP, 12227-010, Brazil

[3] Departamento de Biologia, Universidade de São Paulo, Ribeirão Preto SP, 14040-901 Brazil

[4] Land Surface-Atmosphere Interactions, Technical University of Munich, Freising, 85354, Germany

[5] Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultura, Universidade Estadual de Campinas, Campinas SP, 13083-886, Brazil

Correspondence to: David M. Lapola (dmlapola@unicamp.br)

Abstract. Climate in the Amazon region is particularly sensitive to surface processes and properties such as heat fluxes and vegetation coverage. Rainfall is a key expression of land surface-atmosphere interactions in the region due to its strong dependence on forest transpiration. While a large number of past studies have shown the impacts of large-scale deforestation on annual rainfall, studies on the isolated effects of elevated atmospheric CO_2 concentration (eCO_2) on canopy transpiration and rainfall are scarcer. Here for the first time we make a systematic comparison of the plant physiological effects of eCO_2 and deforestation on Amazon rainfall. We use the CPTEC-Brazilian Atmospheric Model (BAM) with dynamic vegetation under a $1.5xCO_2$ and a 100% substitution of the forest by pasture grassland, with all other conditions held similar between the two scenarios. We find that both scenarios result in equivalent average annual rainfall reductions (Physiology: -252 mm, -12%; Deforestation: -292 mm, -13%) that are well above observed Amazon rainfall interannual variability of 5.1%. Rainfall decrease in the two scenarios are caused by a reduction of approximately 20% of canopy transpiration, but for different reasons: eCO_2-driven reduction of stomatal conductance in Physiology; decreased leaf area index of pasture (-66%) and its dry-season lower surface vegetation coverage in Deforestation. Walker circulation is strengthened in the two scenarios (with enhanced convection over the Andes and a weak subsidence branch over east Amazon) but, again, through different mechanisms: enhanced west winds from the Pacific and reduced easterlies entering the basin in Physiology, and strongly increased easterlies in Deforestation. Although our results for the Deforestation scenario are in agreement with previous observational and modelling studies, the lack of direct field-based ecosystem-level experimental evidence on the effect of eCO_2 in moisture fluxes of tropical forests confers a considerable level of uncertainty to any projections on the physiological

effect of eCO_2 on Amazon rainfall. Furthermore, our results highlight the responsibilities of both Amazonian and non-Amazonian countries to mitigate potential future climatic change and its impacts in the region driven either by local deforestation or global CO_2 emissions.

1 Introduction

Despite the consensual increase in temperature projected for the tropics in the next decades, future precipitation patterns for the region, including even anomaly signals, are still highly uncertain (IPCC, 2013). Such an uncertainty is particularly relevant for the Amazon region, given not only its dependence on small-scale convection but also due to the strong dependence of the region's climate on surface processes (Kooperman et al., 2018). It is now known that the long recognized moisture recycling is a key process in the functioning of the Amazonian system (Eltahir & Bras, 1994), reaching values of up to 80% of recycled precipitation in the west part of the basin (Spracklen et al., 2012; Zemp et al., 2017). As such, alterations in the land surface cover, properties and dynamics are supposed to drive changes in regional climatic patterns.

Past modelling exercises have shown that large-scale clear-cut deforestation of the Amazon and its substitution by pasture or soybean cultivation leads to substantial increase in surface's Bowen ratio, an increase in surface temperature of 2.5ºC to 3.1ºC, with accompanying reduction in the provision of humidity to the atmosphere through evapotranspiration and changes in regional atmospheric circulation and convection, ultimately leading to reduced precipitation of about 25% (in the projections where 100% of the forest is substituted by pasture) (Feddema et al., 2005; Lawrence & Vandecar, 2015; C. A. Nobre et al., 1991; Sampaio et al., 2007; Spracklen & Garcia-Carreras, 2015). The study by Lorenz et al., (2016) shows the importance of the considered scale of deforestation and whether adjacent areas – which experience an increase in horizontal moisture advection – are considered or not. Other studies have covered the multi-directional dynamic feedbacks between climate and resilience of the forest, showing the determining role of the background climate in which deforestation occurs (Li et al., 2016) and oceanic circulation patterns (Cox et al., 2004; P. Nobre et al., 2009) to assess any changes in the vegetation-climate equilibrium for the Amazon region. There is now modelling evidence even on the teleconnections of such an Amazon deforestation-driven climate change, for example with reduced precipitation in Northwest U.S. through the propagation of Rossby Waves (Lawrence & Vandecar, 2015; Medvigy et al., 2013).

Recent studies are now focusing on how more subtle changes in forest dynamics can possibly affect the climate in the region and elsewhere. Splitting up the effects of increased atmospheric CO_2 (eCO_2) into its physiological effects on vegetation (the so called ß sensitivity factor) from the climate sensitivity to eCO_2 (α), and thereafter, the impact of climate on the vegetation (γ), unveils how much of the future climate in the Amazon will be controlled by ecophysiological processes or by physical processes (Betts et al., 2007; Cao et al., 2010; Kooperman et al., 2018). The work by Kooperman et al. (2018) for example shows that the ß effect alone drives stronger reduction in precipitation in the Amazon regions (12%) than the γ effect alone (5%). Such a precipitation reduction caused by the ß effect is driven primarily by a reduced stomatal conductance resulting from eCO_2 in the employed Earth system model (CESM; (Lindsay et al., 2014)). Therefore, despite the persistence of the

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Amazon forest vegetation in these simulations, the flux of moisture from the land surface to the atmosphere is considerably altered, as in the large-scale deforestation modelling exercises. Notwithstanding, there is no set of coupled land surface-atmosphere simulations assessing both the ß and large-scale deforestation effects on climate using the same model(s) and with identical boundary conditions.

Here we perform and systematically compare coupled model simulations on the feedbacks between the Amazon forest vegetation and the regional climate driven either by the physiological effects of eCO_2 on vegetation or by a large-scale Amazon deforestation with its substitution by pasture. Such an exercise allows the timely comparison of the ecophysiological and physical mechanisms involved in the resulting climatic changes from both scenarios of land surface change, which are so far assessed separately in the literature (e.g. (Langenbrunner et al., 2019)). Moreover the present study also provides baseline hypotheses to be tested in the oncoming Free-Air CO_2 Enrichment (FACE) experiment in the central Amazon (Norby et al., 2016). Furthermore, it ultimately draws a timely comparison on the climatic impacts of local direct anthropogenic disturbances such as deforestation, of well-determined responsibility and more feasible to resolve (Nepstad et al., 2014), with a global indirect "disturbance" such as eCO_2, which has a diffuse responsibility and is proving much harder to abate.

2 Methods

2.1 Climate models

This study is focused majorly in the application and analysis of results from the CPTEC-BAM coupled dynamic vegetation-atmosphere model. The CESM model is employed as a parallel model to test specifically the effects of deforestation and compare it to other studies that employed this model to evaluate the physiological effects of eCO_2 on Amazon rainfall (e.g. Kooperman et al. 2018).

CPTEC-BAM is a global atmospheric model of the Center for Weather Forecast and Climatic Studies (CPTEC) from Brazil's National Institute for Space Research (INPE), with a horizontal spectral grid T62 (~ 1.875° lat × 1.875° lon) and 28 vertical levels (hybrid sigma-pressure coordinate, with sigma close to the surface, pressure at the top of the atmosphere). Previous studies (e.g. (Cavalcanti et al., 2002; Marengo et al., 2003)) showed that this model was able to simulate the main climatic features of the South America, although some systematic errors still remain, such as the wet biases over Andes. The land surface component of CPTEC-BAM is the Integrated Biosphere Simulator – IBIS (Foley et al., 1996; Kucharik et al., 2000). (Foley et al., 1996; Kucharik et al., 2000). The estimation of stomatal conductance (g_s) in IBIS is based on the model by Ball & Berry (1982) with an equation (Eq. 1) that describes the response of g_s to carbon assimilation rate (A_n), relative humidity (h_s) and atmospheric CO_2 concentration (c_s) (Collatz et al., 1991):

$$g_s = \mathrm{m}\frac{A_n h_s}{c_s} + b \,, \qquad (1)$$

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where *m* and *b* are respectively the slope and intercept coefficients obtained by analysing the linear regression of leaf gas exchange data in an environment with controlled ventilation and temperature (J. T. Ball et al., 1987). Coefficient *m* has a value of 11 and 4 respectively for tropical evergreen forest and tropical (C^4) grassland. Coefficient *b* has a value of 0.01 for tropical evergreen forest and 0.04 for C^4 grass. Hydraulic-stress control over stomatal conductance is considered through a multiplying parameter based on soil water moisture, ranging from 0 to 1.

CESM is an Earth system model developed by the NCAR and provides simulations of the Earth's climate (Hurrell et al., 2013). CESM is composed of five separate models representing the Earth's atmosphere (Community Atmosphere Model version 5-CAM5), ocean (Parallel Ocean Program-POP version 2), land (Community Land Model 4.5-CLM4.5), land-ice (Glimmer ice sheet model - G- CISM) and sea-ice (Community Ice CodE - CICE4). These components communicate with each other through a central coupler component. The CESM system allows several resolution configurations and combinations of components, which includes making simulations with only the surface component, or the surface coupled with the atmospheric model, among many other combinations. The spatial resolution used is 0.9º lat x 1.25º long, or approximately 100 km of spatial resolution.

2.2 Modelling protocol

The numerical experiments employed here include simulations considering the increase in the concentration of atmospheric CO_2 affecting plant transpiration and experiments considering deforestation in the Amazon as follow (Table 1):

<u>Control</u>: Control runs with atmospheric CO_2 of 388 ppmv.

<u>Physiology</u>: Sensitivity run with a CO_2 concentration of +200 ppmv, equivalent to an increase in 1.5x from control CO_2 value and equivalent to the concentration to be used in the AmazonFACE experiment (Norby et al., 2016). This concentration affects only plant physiology and not radiative balance of the atmosphere.

<u>Deforestation</u>: Sensitivity run with deforestation of the Amazon, where the original forest cover is 100% replaced by C^4 grass pastureland (Fig. 1).

For all model runs sea surface temperature was considered as the climatological mean for the 1981-2010 period. In the experiments with increasing CO_2, the dynamic vegetation scheme was turned on, meaning that vegetation distribution could vary throughout model run, according to the variations of the climatic variables (given that our analysis is focused on precipitation patterns over the Amazon region, dynamic vegetation changes are not analysed here, especially because in fact there are no significant changes of broadleaf forest to other vegetation type in the eCO_2 runs). On the other hand, dynamic vegetation is disabled in the experiments for deforestation of the Amazon rainforest, and the C^4 grass vegetation was prescribed and constant until the end of the integration. Numerical experiments with dynamic vegetation were integrated for a period of 100 years, with constant CO_2 concentration as prescribed in Table 1. Both control and sensitivity runs for the Deforestation scenario were run for a period of 30 years given that these runs employed static vegetation. Analysis of all scenarios relied on averaged results in the last 30 years of simulation.

Similar "Control" and "Deforestation" experiments were carried out using the CESM model, for a comparison with the "Physiology" run done using this model in other studies (Cao et al., 2010; Kooperman et al., 2018). These CESM simulations were configured with only the atmospheric and land surface components enabled, to produce simulations that could be also comparable with CPTEC-BAM.

3. Results

Figure 2 shows that both eCO2 and deforestation lead to considerable reduction in precipitation across the Amazon region, especially in east and central Amazon in the Physiology and Deforestation scenarios with CPTEC-BAM. Two remarkable differences between the Physiology and Deforestation runs regarding the spatial pattern of precipitation changes is the extension of the reduction area over Bolivia and south Peru in the latter model run and the strong localized precipitation increase over Colombia and Venezuela in the former model scenario. In fact average precipitation reduction with CPTEC-BAM is slightly stronger in Deforestation than in the Physiology scenario: -0.80 mm d^{-1} against -0.69 mm d^{-1} (Fig. 3a), which represent respectively 14% and 12% of the region mean annual precipitation.

As expected for a tropical region where variations in precipitation and temperature are tightly coupled, the reduction in precipitation leads to an increase in regional temperature – which is 1.2ºC stronger in the Physiology scenario than in the Deforestation scenario (Fig. 3b). Although changes in moisture budget are similar for all three scenarios, we attribute the comparatively moderate change in near surface atmospheric temperature and sensible heat in the Deforestation scenario as a result of a strong increase in near-surface atmospheric advection (presented in section 3.2). Part of the observed temperature increase in the Deforestation scenario is also a result of albedo increase (0.13 to 0.19). Notwithstanding the substitution of forest by pasture reduces the transference of humidity from the surface to the atmosphere, driving a decrease in latent heat that is comparable to the one observed also in the Physiology run. The reduction of evapotranspiration (Physiology = -0.33 mm d^{-1}; Deforestation: -0.26 mm d^{-1}) alongside with decreased precipitation in both Physiology and Deforestation model scenarios yields a reduction of moisture convergence, which is 48% lower in the Deforestation scenario owned to the slightly stronger reduction of precipitation but smaller reduction of evapotranspiration in this scenario.

3.1 Provision of humidity

The similarity of average precipitation and evapotranspiration changes in the Physiology and Deforestation scenarios reveals the strength of the forest's ecophysiological (*i.e.* stomatal) control on the regional climate. The effect that a higher CO_2 concentration has in reducing g_s (Eq. 1) overcomes the effect positive effect of increased gross primary productivity in g_s, resulting in a net reduction of stomatal conductance in the Physiology run. On the other hand, the decrease in precipitation and evapotranspiration obtained in the Deforestation run is a result of the lower g_s that is maintained by C4 grasses, the integration of this lower g_s over a canopy with lower leaf area index (compared to broadleaf tropical forest) and a decreased gross primary productivity. Notwithstanding, a counter intuitive increase of specific moisture along the vertical atmospheric

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profile is found in the Full and Physiology model runs with CPTEC-BAM, whereas the same model shows a decrease in specific humidity in the Deforestation run.

3.2 Atmospheric circulation

As previously modelled in the study by Kooperman et al. (2018) using CESM, eCO_2 causes convective heating over Central Africa that drives anomalous eastward flows across the tropical Atlantic Ocean, ultimately affecting the flow of humidity into the Amazon basin (Fig. 5). In fact there is also a strengthening of the Walker cell in CPTEC-BAM over the Amazon region, with increased moisture convergence in north South America (also helped by stronger westerlies from the Pacific in this region), not as strong as in CESM, but sufficient to result in precipitation increase in north Andes, and atmospheric stabilization with precipitation decrease across most of the Amazon.

Atmospheric circulation changes are completely different in the deforestation scenario (Fig. 5c), in which there is a pronounced increase in easterlies across the entire Amazon region as a result of decreased roughness length of surface vegetation [2.65m in tropical evergreen forest and 0.08m in C^4 grass (Sampaio et al., 2007)], and also reduced pumping of deep soil moisture to the atmosphere, namely in the dry season (June to October) (Fig. 6d). This latter causes a strong moisture convergence such that winds even surpass the Andes (causing precipitation there) and enter the Pacific.

The reduction of latent heat flux in all three scenarios also helps reduce convection over the Amazon region, which tends to cool the upper atmosphere, reinforcing atmospheric stabilization.

These changes in horizontal circulation imply that less moisture enters the Amazon region from the Atlantic, and less moisture leaves the regions towards the Andes (this latter is somewhat compensated by a stronger moisture convergence from the Pacific to the Andes). The Deforestation run presents a distinct result regarding the in- and outflow of humidity in the region: while there is a moderate increase in the input from the eastern Amazon border, there is a reversion of the flux in the northern border, with significant humidity leaving the region from there and also from the western border towards the Andes and Pacific. On the other hand there is a 4-fold increase in the horizontal moisture flux out of the region from its southern border towards the Plata river basin. This moisture-flux increase across south Amazon is slightly stronger in the deforestation scenario, as a result of the strengthened easterlies and its Andes-driven southeast turn nearby Bolivia.

3.3 Seasonality

Precipitation is consistently below control values year round for all three experimental model runs, with a single exception of December's value in the Deforestation scenario (Fig. 6a). However, differences regarding monthly precipitation between Full/Physiology and Deforestation scenarios are evident at the end of the dry season and onset of the rainy season (August to December). In this regard, precipitation seasonality is stronger in the Deforestation scenario compared to the Physiology and Full model runs. This is closely linked to changes in evapotranspiration given that the permanence of the forest in the Physiology scenario supports a higher evapotranspirative flux along the dry season compared to the Deforestation run (Fig.

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6c). On the other hand evapotranspiration values in the Deforestation run are close to the control values throughout the rainy season, which explains partly the comparatively moderate increase in temperature in this scenario

These seasonal variations in evapotranspiration are at least partly explained by the opposing seasonal patterns of canopy transpiration in the Physiology and Deforestation scenarios (Fig. 6d). At the one hand the highest values of this variable in the Physiology run occur during the dry season, when high vapour pressure deficit increases evapotranspirative demand that trees can fulfil (at least partially) even under eCO_2. On the other hand, the lowest values of canopy transpiration in the Deforestation run occur during the dry season, as a result of seasonal decrease in pasture leaf area index and root depth in this scenario.

Stomatal closure driven by eCO_2 leads to higher water use efficiency (the amount of water used [in transpiration] per unit of carbon assimilated through photosynthesis), but even so there is a small decrease (~2%) of available soil water in the Physiology scenario, due to the increase in temperature and evaporation. This decrease is more pronounced in the Deforestation run (reaching a reduction of 30% at the peak of dry season in September), due to the fact that pasture coverage decreases from rainy to dry season, from a vegetation coverage fraction of 0.9 to 0.5, which, together with evapotranspiration and the decreased input of rainwater, act to decrease soil water in the dry season in the Deforestation scenario (Fig. 6e).

4. Discussion

Our results show that the modelled responses to eCO_2 and large-scale deforestation lead to equivalent reductions of annual average precipitation and evapotranspiration in the Amazon region. The simulated decreases in precipitation (Physiology: 12%; Deforestation: 13%) are well beyond Amazon region rainfall interannual variability of 5.1% (Spracklen & Garcia-Carreras, 2015). Different climatological mechanisms drive such reductions in the two scenarios. Both scenarios have in common that the mechanism behind precipitation reduction is the reduced flux of moisture from surface vegetation to the atmosphere. The difference, however, is that in the Physiology scenario due to an eCO_2-driven reduced stomatal conductance, whereas in the Deforestation scenario it is due to reduced g_s inherent to C^4 photosynthetic pathway of tropical pasture grass, decrease of leaf area index, and a dry-season reduction in surface vegetation coverage. Another similar mechanism of change in both scenarios is the strengthening of the Walker cell over the Amazon, with a subsidence branch over east Amazon and a region of enforced convection by the west/northwest. On the other hand, different patterns of change in near-surface horizontal circulation (driven by distinct roughness lengths of tropical forest and pasture) imply substantial difference between the two scenarios in respect to atmospheric moisture content and temperature over the Amazon region.

In fact the enhancement of the Walker circulation in both scenarios takes place due to different reasons. In the deforestation scenario it is due to the strong intensification of the easterlies (Hadley Cell) across the Amazon and up to the Andes. In the Physiology scenario two atmospheric circulation changes take place: on the one side the intensification of west winds from the Pacific increases precipitation over the Andes, especially in north South America; on the other hand the decrease of trade

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winds (weakening of the Hadley Cell), which is apparently due to a combination of a regional redistribution of convection and moisture converge/divergence and a teleconnection with eCO2-driven climatic changes in tropical Africa, this latter also shown by Kooperman et al. (2018). These results are corroborated by previous studies on the modelled effect of eCO_2 and deforestation on climate, though using different models and model setups (i.e. not systematically comparing the effect of both drivers using the same model(s) and following a single modelling protocol).

Deforestation run using CESM resulted in equivalent precipitation reduction (-0.7 mm $d^{-1;}$ -12%) compared to other studies that employed CESM/CLM to test the effects of eCO_2 on Amazon rainfall (Cao et al., 2010; Kooperman et al., 2018). However, CESM simulation yielded a different spatial pattern of rainfall change compared to CPTEC-BAM, with stronger reduction/increase of precipitation in east/west Amazon (Fig. 7), associated with a more pronounced strengthening of the Walker circulation and cooling or the Amazon atmospheric column, as explained previously in the study by Badger & Dirmeyer (2016) using CESM. Rainfall change mechanisms are therefore similar in CPTEC-BAM and CESM.

4.1 Deforestation and rainfall in the Amazon

There is a long-known and overwhelming agreement between models that whole-basin deforestation of the Amazon leads to a warmer (average of 1.9ºC [±1.8ºC] vs. 0.93 in the current simulation with CPTEC-BAM) and drier (average -15% vs. -13% in CPTEC-BAM) climate over the region, driven namely by increase in trade-winds due to the considerably smaller roughness length of pastures (Lawrence & Vandecar, 2015; Sampaio et al., 2007; Spracklen & Garcia-Carreras, 2015; Sud et al., 1996). Fully interactive coupling between the atmosphere and oceans results in twice the rainfall reduction in comparison to non-coupled simulation such the present study (Nobre et al., 2009). Although previous modelling and observation studies [e.g. (Saad et al., 2010; Silva Dias et al., 2002)] have shown that small-scale deforestation leads to localized increase in rainfall, there is now modelling and observational evidence that widespread and large-scale deforestation in the Amazon drives rainfall reductions (Lawrence & Vandecar, 2015; C. A. Nobre et al., 2016; Sampaio et al., 2007) and/or a lengthening of the dry season (Dubreuil et al., 2012; Fu et al., 2013). This latter effect is also in line with our results (Fig. 6a).

While the conceptual model proposed/reviewed by Lawrence & Vandecar (2015) suggest that whole-basin deforestation should lead to rainfall reductions of >30%, we argue that the longitudinal gradient in rainfall recycling should be considered in these estimates: the rainfall reductions observed with CPTEC-BAM in both the Deforestation and Physiology scenarios is within the estimated range of precipitation recycling of east Amazon [10% - 30% (Zemp et al., 2017)], which is the region where the subsidence branch of the Walker cell acts more strongly in these simulations.

4.2 CO_2 fertilization effect and moisture fluxes in the tropics

Differently from the effect of deforestation on Amazon rainfall, observational or experimental evidence on the effects of eCO_2 on water fluxes in tropical forests are scarce. Most of the knowledge on the ecosystem-scale effects of eCO_2 comes from low diversity temperate forests (Ainsworth & Long, 2005; Aisworth & Rogers, 2007; De Kauwe et al., 2013), laboratory studies with seedlings or saplings [e.g. (Aidar et al., 2002)], or growth rings from trees at the fringes of tropical

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forests (van der Sleen et al., 2014). In that sense, for example, the +150ppm Oak Ridge Free-Air CO_2 Enrichment (FACE) experiment in broadleaf temperate forest resulted in an average reduction of transpiration of 17% (De Kauwe et al., 2013). A reduction of 20% in stomatal conductance was found in the +150ppm, single-species, eucalyptus FACE (EucFACE) in New South Wales woodlands, Australia (Gimeno et al., 2016). Both results are comparable to the 20% reduction of transpiration found in the Physiology scenario. However, water-use efficiency (calculated here as the ratio between NPP and transpiration) increased 35% in the 11-year long Oak Ridge FACE, and 30-35% in the 1850-2000 period as assessed from growth rings from trees at the fringes of tropical forests (van der Sleen et al., 2014). Our simulation yielded a much higher value of 128% in the Physiology scenario, owned to a stronger increase in NPP in CPTEC-BAM (+13% in Oak Ridge FACE; +75% in CPTEC-BAM). Although the temperature dependence of Rubisco kinetics imply that eCO_2 effects on NPP in the tropics should in principle be stronger (Hickler et al., 2008), NPP in CPTEC-BAM seems to be oversensitive to eCO_2, as is the case also for other vegetation models that do not consider nutrient cycling (De Kauwe et al., 2013). Phosphorus for example is a highly limiting nutrient in Amazon soils and the consideration of such a limitation would decrease the expected eCO_2-induced gains in GPP and NPP simulated by models without nutrient constraints respectively by 42% and 50% after 10 years (Fleischer et al. 2019). Observations from the strongly P-limited EucFACE site even showed a 5% reduction in the NPP of mature *Eucalyptus tereticornis* stands after 4 years of CO_2 fertilization (Jiang et al., 2020). Should our simulations consider the combined effect of P limitation, stomatal conductance and therefore canopy transpiration would be even lower and Amazon rainfall reduction could be even stronger in the Physiology scenario compared to the Deforestation scenario.

One must also consider that in a hyper-diverse ecosystem such as the Amazon forest the response to eCO_2 in terms of stomatal conductance may vary considerably from one tree species to another, or from a functional group/strategy of trees to another (Domingues et al., 2014). It is now known that different Amazon tree species can have rather different strategies regarding water usage and saving (Bonal et al., 2000). Such a variety of responses and more subtle implications of eCO_2 on the Amazon forest functioning is yet to be incorporated in vegetation models or surface schemes (Lapola, 2018).

Therefore, even if our results for the Physiology scenario are aligned with observational results from non-tropical forest ecosystems and modelling results [namely from the studies by Cao et al. (2010); Kooperman et al. (2018)], there is a considerable level of uncertainty in the Physiology scenario projection of CPTEC-BAM [and also of CESM (Cao et al., 2010; Kooperman et al., 2018)]. This level of uncertainty shall stay as such until there is direct field-based data on the ecosystem-level effects of eCO_2 in the Amazon forest (Norby et al., 2016).

As such we suggest that future research on this topic should focus on gathering such field-based experimental evidence on the ecosystem-level effects of eCO2 in the Amazon forest. Additionally, the basin-wide effects eCO_2 on Amazon rainfall should be projected with models that consider the potential limitations by soil phosphorus and also interacting oceans.

Lastly, the similarity of results obtained for rainfall and evapotranspiration reduction with CPTEC-BAM under a $1.5xCO_2$ experiment and the results from CESM under $2xCO_2$ (Cao et al., 2010) and $4xCO_2$ (Kooperman et al., 2018) scenarios might be a result first of the strong sensitivity of NPP and stomatal conductance to eCO_2 in CPTEC-BAM, but also a consequence of the saturation of eCO_2 effects on stomatal conductance that takes place between 600 and 1000 ppmv, as shown for a variety of plant species with instantaneous measurements [e.g. (Domingues et al., 2014; Zheng et al., 2019)], although long-term (beyond the execution time of FACE experiments) acclimation changes of g_s to eCO_2 are yet poorly known (Xu et al., 2016).

4.3 Mitigation perspectives

One should interpret the implications of the results presented here with care, considering the different responsibilities involved in the two anthropogenic disturbances considered in this modelling exercise – deforestation and elevated atmospheric CO_2 concentration. Avoiding the significant rainfall reductions projected here involves halting deforestation in the Amazon and reducing global CO_2 emissions or actively removing it from the atmosphere. On the one side the curbing of deforestation in the Amazon is something that invariably has to be carried out by different actors within the nine Amazonian countries (France/French Guyana included), though international markets and institutions can play an important role as well (Nepstad et al., 2014; Rajão et al., 2020). On the other side, the increase of atmospheric CO_2 concentration is a global process, the mitigation of which demands a concerted effort by all countries, namely historical and current top-emitters (Peters et al., 2015). In this sense, even if Amazon deforestation is stopped sometime soon in the future, forest functioning and structure can still be jeopardized by eCO_2 and consequent climatic changes. Therefore, while both anthropogenic disturbances – deforestation and elevated atmospheric CO_2 concentration – lead to equivalent reductions in Amazon rainfall, this result should be interpreted as evidence that both regional and global responsibilities are at stake to mitigate potential future climatic change and its impacts in the region (Lapola et al., 2018).

5. Conclusions

In this study we have, for the first time, applied a single coupled climate-vegetation model and standardized modelling protocols to simulate the comparative impacts of the physiological (ß) effect of eCO_2 ($1.5xCO_2$) and large-scale (100%) deforestation on precipitation in the Amazon region. Our results show equivalent decreases of average annual precipitation for the two scenarios (Physiology or ß: 12%; Deforestation: 13%) that are well above the interannual variability of precipitation in the Amazon of 5%. The two scenarios also yield reductions in average annual evapotranspiration rates (Physiology or ß: -0.33 mm d^{-1}; Deforestation: -0.29 mm d^{-1}). Such a decreased input of moisture to the atmosphere is caused by an eCO2-driven reduction in stomatal conductance that ultimately causes a 20% reduction in canopy transpiration in the Physiology scenario. In the Deforestation scenario the reduction of moisture flux from the vegetation to the atmosphere is caused by the reduced stomatal conductance inherent to C4 plants, smaller leaf area index of pastures and a dry-season decrease in surface vegetation coverage. In both scenarios there is a strengthening of the Walker circulation over tropical South America, with a convection zone concentrated over the Andes and a weak subsidence over east Amazon. However, the mechanisms driving such a redistribution of convection within the Walker cell are different for each of the two scenarios. In the Physiology run it is both the strengthening of west winds coming from the Pacific that increases rainfall in this region

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and even leads to an increase of atmospheric specific humidity over west Amazon, and a weakening of the Atlantic easterlies entering the Amazon basin due to the increased convection over Colombia and Venezuela and in tropical Africa. On the other hand in the Deforestation scenario it is the considerable reduction of surface roughness length that drives a strong increase of the easterlies flowing over the Amazon region that ultimately leads to the strengthening of Walker circulation. Our results for the Deforestation model run are in close agreement with previous observational and modelling studies. However, while our results for the Physiology scenario are at least partly aligned with observational studies in non-tropical forests, data on growth rings from tropical trees, and other modelling studies, there is no direct, field-based experimental evidence on the ecosystem-level effects of eCO_2 on moisture fluxes (and other processes) in the Amazon forest, which confers a considerable level of uncertainty to these and other simulations on the ß effect of eCO_2 in the Amazon [e.g. (Kooperman et al., 2018)]. All in all, even if deforestation is completely stopped soon the world's largest tropical forest and its climate system can still be jeopardized by eCO_2, ultimately depending on a process happening at leaf stomata (Berry et al., 2010). Considering that the curbing of deforestation is a local/regional process (though tied to international markets and institutions), and that ramping atmospheric CO_2 concentration is a global process, the reduction of which demands a concerted effort by all countries, it is clear that the responsibilities of Amazonian and non-Amazonian countries are at stake to mitigate the climatic changes projected here.

Data availability

Computational codes from the models employed here and their outputs used in this study will be made available upon acceptance of this manuscript for publication.

Author Contribution

GS, MC, CvR, LFR and DML designed the study; CAGJ and FA carried out model runs and organized data curation; MS helped in the preparation of figures and analysis of data; MS, DML and GS prepared original manuscript draft; TD, AR, CvR, LFR and DML reviewed and edited earlier versions of the manuscript; GS and DML acquired funding; DML coordinated the project which this study is related to.

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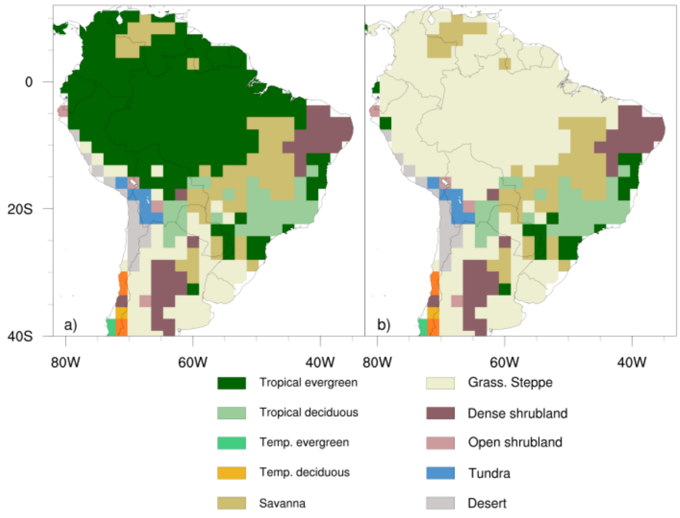

Figure 1: Vegetation maps used in (a) Physiology and (b) Deforestation modelling scenarios. Vegetation type grass. steppe in the Amazon region is composed of C[4] grass, representing tropical pasturelands.

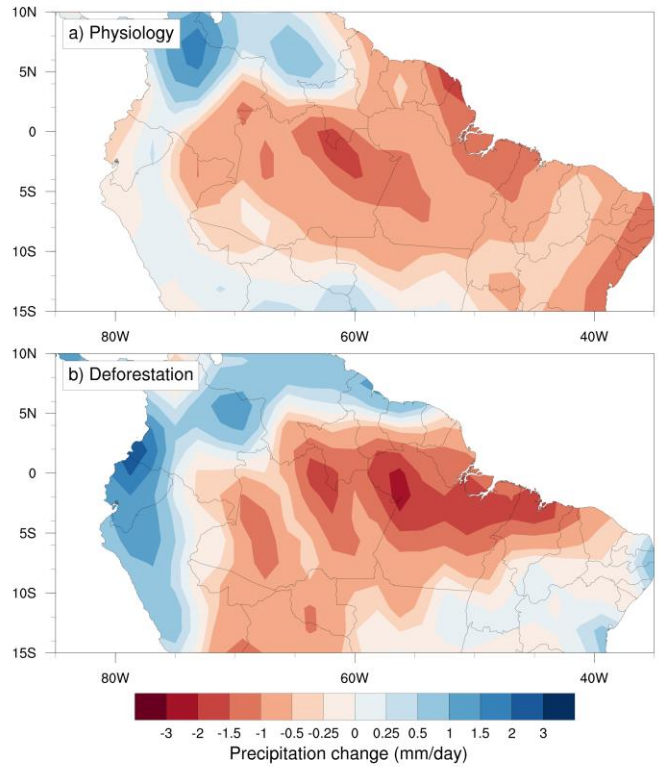

Figure 2: Annual mean precipitation change relative to control simulations using the CPTEC-BAM in tropical South America under (a) an atmospheric CO_2 concentration of +200 ppmv (1.5xCO_2) affecting solely surface vegetation physiology (Physiology), and (b) with complete substitution of the Amazon forest by pasture grasslands and a control CO_2 concentration of 388ppm (Deforestation).

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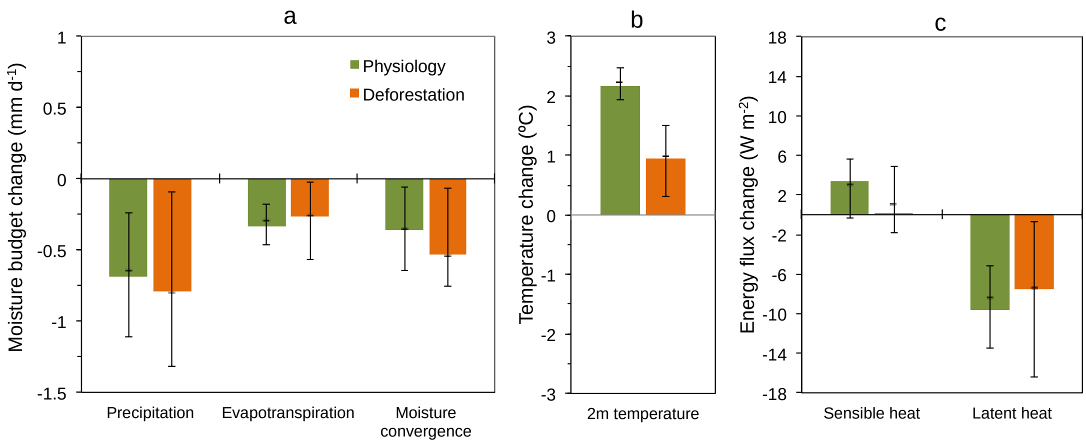

Figure 3: Mean annual changes in (a) moisture budget, (b) 2m-air temperature and (c) energy balance from the CPTEC-BAM over the Amazon region (black line square in Fig. 5) under an atmospheric concentration of +200 ppmv (1.5xCO_2) affecting solely surface vegetation physiology (Physiology), and complete substitution of the Amazon forest by pasture grasslands (Deforestation). Solid lines indicate the interquartile range (25th, 50th and 75th percentile values) based on the spatial variability from gridpoints used in the regional average.

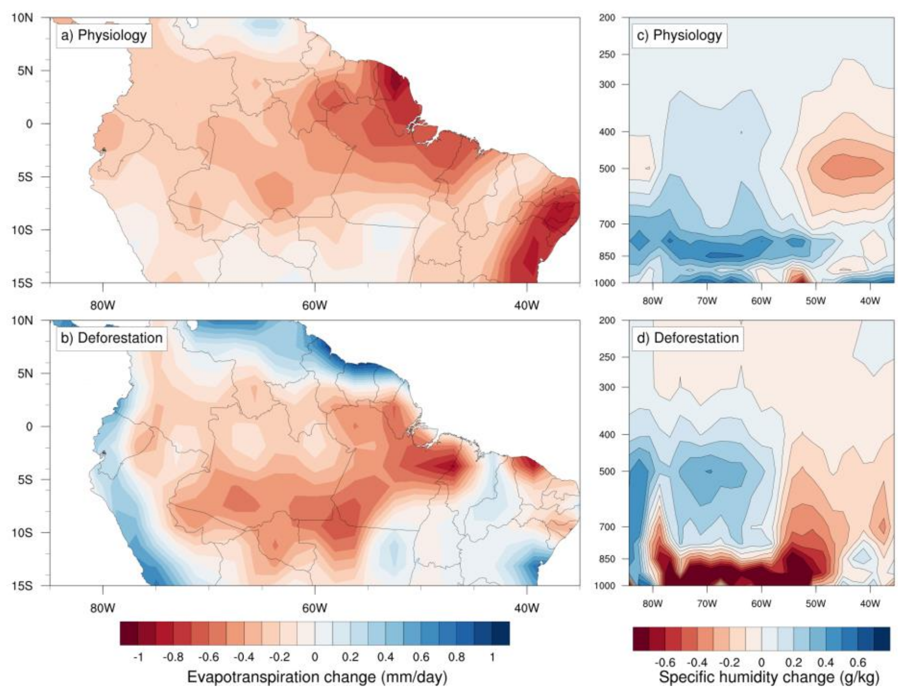

Figure 4: Annual mean changes in evapotranspiration (a-b) and meridional mean specific humidity vertical profile (with pressure in mb as vertical coordinate) (d-e) in tropical South America under an atmospheric concentration of +200 ppmv (1.5xCO_2) (a, d) affecting solely surface vegetation physiology, and (b, e) with complete substitution of the Amazon forest by pasture grasslands.

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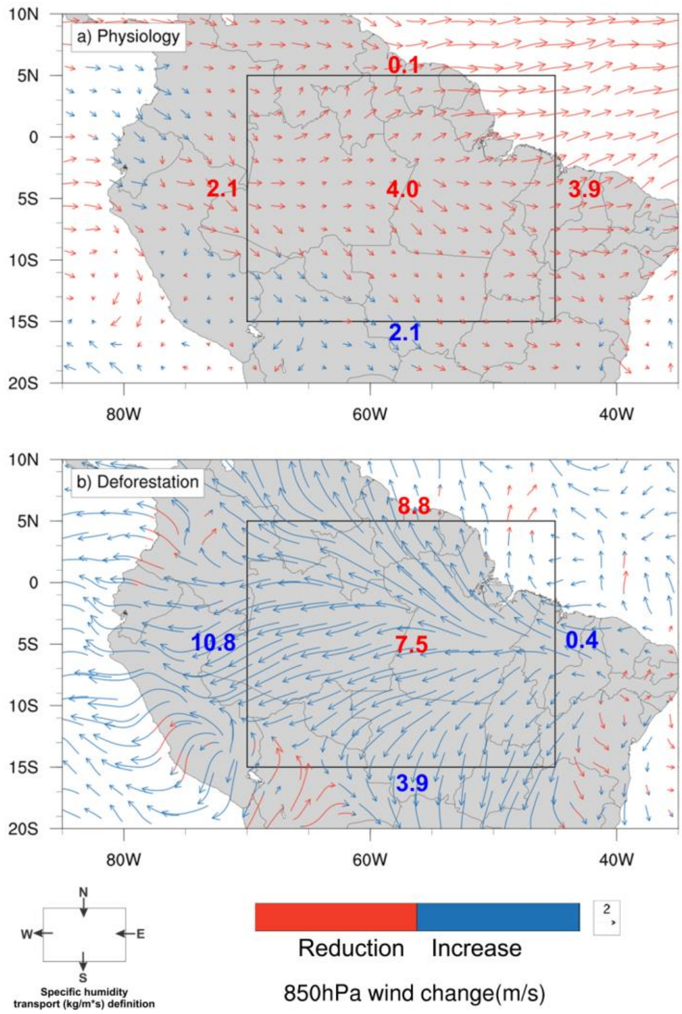

Figure 5: Annual mean changes in 850 mb horizontal wind in tropical South America under an atmospheric concentration of +200
530 **ppmv (1.5xCO_2) (a) affecting both solely surface vegetation physiology, and (b) with a complete substitution of the Amazon forest by pasture grasslands. Black square depicts the region over the Amazon for which changes in the specific humidity flux balance (kg m^{-1} s^{-1}, integrated up to 500mb) is calculated. Red and blue arrows/numbers represent respectively decrease and increase of the given variable.**

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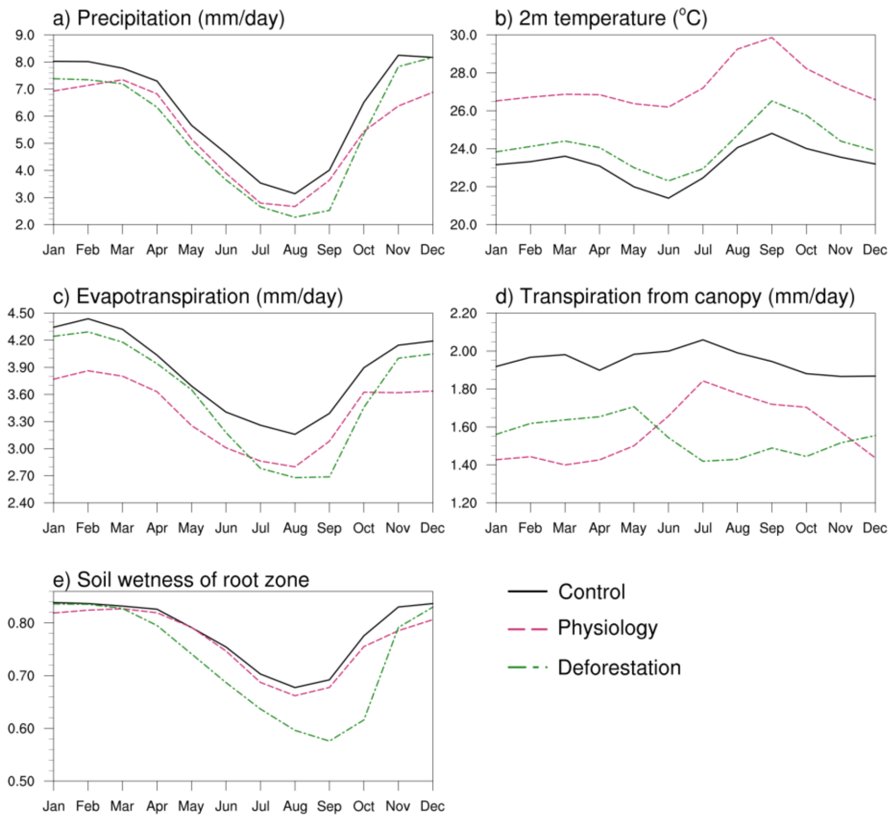

Figure 6: Mean monthly precipitation, 2m-temperature, evapotranspiration, canopy transpiration and topsoil water content in the Amazon region (black line square in Fig. 5) in the Control, Physiology and Deforestation modelling scenarios.

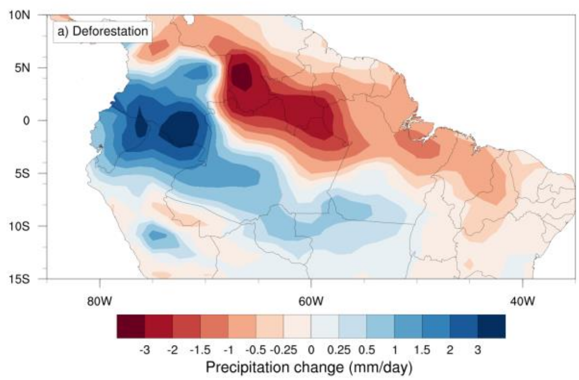

Figure 7: Annual mean precipitation change relative to control simulation using CESM in tropical South America with complete substitution of the Amazon forest by pasture grasslands.

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545 **Table 1: Numerical experiments performed with CPTEC-BAM.**

Experiment	Vegetation	CO_2 concentration (ppmv)		Deforestation
		Atmosphere	**Land Surface**	
Control	Dynamic/Static*	388	388	No
Physiology	Dynamic	388	588	No
Deforestation	Static	388	388	Yes

*Control run with static vegetation was used for comparison with the Deforestation run.