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

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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: -2572 mm, -12%; Deforestation: -292183 mm, -139%) that are well above observed Amazon rainfall interannual variability of 5.1%. Rainfall decrease in the two scenarios are caused bylinked to a reduction of approximately 20% of canopy transpiration, but for different reasons: eCO_2-driven reduction of stomatal conductance in Physiology, and decreased smaller leaf area index of pasture (-7266%) and its dry-season lower surface vegetation coverage in Deforestation. Walker circulation is strengthened modified in the two scenarios [(Physiology: a humidity-enriched free troposphere with decreased deep convection due to the heightening of a drier and warmer (+2.1ºC) boundary layer; Deforestation: with enhanced convection over the Andes and a weak subsidence branch over east Amazon without considerable changes in temperature (-0.2ºC)]) but, again, through different mechanisms: enhanced strengthened 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 and 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~~ is associated ~~to~~ with substantial ~~increase~~ changes in surface's Bowen ratio~~,~~ and ~~increase~~ in surface temperature~~,~~ ~~of~~ from -0~~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~~with rainfall reduction~~ precipitation~~ of about 25% (in the projections where 100% of the forest is substituted by pasture) (Feddema et al., 2005; Lawrence and Vandecar, 2015; Lejeune et al., 2015; Nobre et al., 1991; Sampaio et al., 2007; Spracklen and 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; 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 and 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~~associated with 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 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 isolated 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~~ mostly on 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 model simulates the coexistence of both grass and tree plant functional types (PFTs) in grid cells, and disturbances such as fire are represented by a fixed percentage of the biomass of all PFTs that is reduced every year. 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):

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

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 (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~~ physiology and experiments considering deforestation in the Amazon as follow (Table 1):

Control: Control runs with an atmospheric CO_2 concentration of 388 ppmv, one with dynamic and another with static geographical distribution of vegetation types (for comparison with Physiology and Deforestation scenarios respectively)~~.~~.

Physiology: 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 the radiative balance of the atmosphere.

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

RCP8.5+Def: Sensitivity run using RCP8.5's CO_2 increase trajectory affecting both plant physiology and atmospheric radiative balance, with concomitant replacement of 100% of forest cover by C^4 grass pastureland (the results of which are shown in this article's Supplement).

The selection of such scenarios start first with the intention of understanding the impacts on moisture fluxes and rainfall in the Amazon driven by the target concentration to be used in the AmazonFACE experiment in Central Amazon (Norby et al., 2016). Second, we also wanted to know how the results obtained in the Physiology scenario compared to changes due to an extreme deforestation in the region. Rather than representing realistic projections of the future of the Amazon, this systematic separation of climatic forcings allow us to better understand how each of them contribute to future changes in the region. Notwithstanding, an atmospheric CO_2 concentration of +200 ppm (i.e. 588ppm) is projected to be reached short after 2050 under IPCC's RCP8.5 and in 2080 under the RCP6.0 (Vuuren et al., 2011). A complete deforestation of the Amazon basin, following a business-as-usual deforestation-rate scenario – with deforestation rates typical of the late 1990's – could be possibly reached around 2100 (Soares-Filho et al., 2006).

For all model runs sea surface temperature was considered as the climatological mean annual cycle for the 1981-2010 period. In the experiments with increasing CO_2, the dynamic vegetation scheme was turned on, meaning that the geographical distribution of vegetation ~~distribution~~ types 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 held 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 eCO_2 and deforestation ~~lead to~~are associated with a 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~~ Physiology than in the ~~Physiology~~ Deforestation scenario: -0.~~80~~ 70 mm d^{-1} against -0.~~69~~ 50 mm d^{-1} ~~(Fig. 3a)~~, which represent respectively 124% and ~~12~~9% of the region mean annual precipitation~~.~~, even though the variability range of anomalies in both scenarios do not indicate a significant difference between the two mean values (Fig. 3a).

As expected for a tropical region where variations in precipitation and temperature are tightly coupled, the reduction in ~~precipitation~~ evaporative cooling ~~leads to~~and changes in atmospheric circulation ~~an~~ are combined with changes~~increase~~ in regional surface temperature – ~~which is~~ ~~+1.2~~2.1ºC ~~stronger~~ in the Physiology scenario, -0.2ºC ~~than~~ in the Deforestation scenario (Fig. 3b). Although changes in moisture budget are similar for ~~all three~~these two scenarios (Table 2), we attribute the ~~comparatively~~ moderate change in near surface atmospheric temperature and decrease in sensible heat in the Deforestation scenario as a result of a strong increase in near-surface atmospheric advection (~~presented in~~see section 3.2). Part of the observed ~~temperature increase~~evapotranspiration decrease 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: ~~=~~ -0.35~~3~~ mm d^{-1}; Deforestation: -0.~~26~~28 mm d^{-1}) ~~alongside with decreased precipitation in both Physiology and Deforestation model scenarios yields~~ is associated with a reduction of moisture convergence [precipitation minus evapotranspiration (Banacos and Schultz, 2005)] alongside with decreased precipitation in both Physiology and Deforestation model scenarios~~,~~. Reduction in moisture convergence ~~which~~ is 59~~48~~% ~~lower~~ more pronounced in the ~~Deforestation~~ Physiology scenario (Fig. 3a) ~~-~~owned namely to the strong reduction in horizontal transport of humidity by east winds.~~owned to the slightly stronger reduction of precipitation but smaller reduction of evapotranspiration in this scenario~~. The mechanisms associated with these changes are explained next.

3.1 Provision of humidity

The similarity of average precipitation, ~~and~~ evapotranspiration and moisture convergence changes in the Physiology and Deforestation scenarios reveals the strength of the forest's ecophysiological (*i.e.* stomatal) control on the regional climate (Fig. 4). 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 (GPP) (Physiology: +7.0 μmolCO_2 m^{-2} s^{-1} (+58%); Deforestation: -1.0 μmolCO_2 m^{-2} s^{-1} (-16%) in g_s, resulting in a net reduction of stomatal conductance in the Physiology run of -0.10 mol m^{-2} s^{-1} (-26%), which is related to a decrease of -0.35 mm d^{-1} (-18%) in canopy transpiration (Table 2). On the other hand, the decrease in precipitation and evapotranspiration obtained in the Deforestation run (Fig. 4) does not ~~is a~~ result ~~of the~~in a considerably lower g_s that is generally maintained by C^4 grasses (-0.02 mol m^{-2} s^{-1}; -4%). ~~,~~However, the considerable reduction of leaf area index (-72%) ~~the integration of this lower g_s over a canopy with lower leaf area index (compared to broadleaf tropical forest)~~ and a slightly decreased ~~gross primary productivity~~GPP are associated with an average decrease of transpiration (-0.42 mm d^{-1}; -22%) in the Deforestation scenario). Notwithstanding, a counter intuitive increase of specific moisture along the vertical atmospheric profile above the planetary boundary layer is found in the ~~Full and~~ Physiology model run~~s~~ with CPTEC-BAM (+0.32 g kg^{-1}), whereas the same model shows a decrease in specific humidity in the Deforestation run (-0.07 g kg^{-1}) (Fig. 5b and d).

3.2 Atmospheric circulation

As previously modelled in the study by Kooperman et al. (2018) using CESM, eCO_2 causes is related to 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.Fig. S5 shows the meridional mean planetary boundary layer height at the equator over the Amazon under the different scenarios. In the Deforestation scenario there is an average decrease of 10% in the boundary layer height, attributable to the considerably lower surface roughness length of pasture compared to a tropical forest. On the other hand, there is an average increase of 21% in boundary layer height in the Physiology run, associated with the increased heating of surface. The superposition of the spatial pattern of changes in moisture convergence over the 850 hPa-atmospheric circulation anomalies shows that different circulation patterns in produce similar changes in the region's atmospheric moisture budget. As a result eCO_2 causes a higher, drier and warmer boundary layer over the Amazon that acts as a barrier to a humidity-enriched free, though shallower free troposphere with less deep convection (c.f. Langenbrunner et al., 2019). On the other hand, the strong increase in westward moisture advection, aligned with the increased albedo and decreased vertical mixing (Fig. S5) seems to best explain the nearly unchanged surface temperature in the Deforestation scenario.

The reduction of latent heat flux in all three scenariosour simulations (Fig 3c and Table 2) also helps reduce convection over the Amazon region, which tends to cool the upper atmosphere, reinforcing atmospheric stabilization.

These changes in horizontal circulation imply, in the Physiology scenario that less moisture enters the Amazon region from the Atlantic (-4.9 kg m^{-1} s^{-1}), and less moisture leaves the regions towards the Andes (-2.6 kg m^{-1} s^{-1})(this latter is somewhat compensated by a stronger moisture convergence from the Pacific to the Andes, Fig. 5b). In the Deforestation scenario there is an increase of the input of humidity to the Andes at the surface level (in the order of 3.0 kg m^{-1} s^{-1}), which is perceptible also in the west part of the vertical profile of humidity near surface levels (Figure 5d). The lower evapotranspirative capacity aligned with a lower vertical mixing due to pasture's lower roughness length result in an atmospheric volume depleted of moisture and with decreased uplifting of air masses. In the Physiology scenario, despite of the decreased evapotranspirative capacity, the increased surface heating increases vertical mixing at low levels (up to 700hPa) that is associated with a deeper boundary layer and higher mixing layer, which, in turn, is connected to the increase of humidity throughout the free tropospheric volume (above the boundary layer) over the region. However, after such atmospheric height there are strong subsidence anomalies in the Physiology run (Figure 5b), which decreases deep convection that is ultimately associated with lower rainfall rates. The same vertical circulation patterns have been well demonstrated in previous (separate) studies that modeled large-scale deforestation of the Amazon and, more recently, the isolated physiological effects of eCO_2 on the region's climate (*c.f.* Langenbrunner et al. 2019).

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 Radiative balance

A decrease in surface sensible heat (-1.34 W m^{-2}) in shown the Deforestation run (Fig. 3c), which alongside with a decrease in latent heat result in a negative net surface radiation balance in the deforestation run, that is associated with a small decrease in average 2m-air temperature (-0.2 ºC) (Table 2). On the other hand, in the Physiology scenario there an increase in sensible heat (+3.96 W m^{-2}) that is associated with an average increase in 2m-air temperature of +2.1ºC. While the decrease in latent heat is also directly connected to a lower evapotranspiration, the opposite results shown in each scenario regarding sensible heat is associated with also opposite changes in near-surface atmospheric circulation patterns: in the Deforestation run there is a increase in near-surface atmospheric advection, whereas in the Physiology scenario this advection is considerably decreased (as explained in section 3.2 Atmospheric circulation). Shortwave radiation is increased due to decreased nebulosity in both model scenarios (Physiology: -1.4%; Deforestation: -2.2%), but such an increase in shortwave radiation balance is stronger in the Deforestation scenario due to the albedo change. The same pattern is also obtained for the surface balance of longwave radiation, which increases in both scenarios, but more strongly in the Deforestation (Physiology: 2.7 W m^{-2}; Deforestation: 6.9 W m^{-2}), which is probably a combination of lower evapotranspirative capacity and increased horizontal advection in the latter scenario.

3.3 4 Seasonality

Precipitation is consistently below control values year round for all threethe Physiology and Deforestation experimental model runs, with a single exception of December's value in the Deforestation scenario (Fig. 6a and S4a). 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 run~~s~~. 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. 6c). On the other hand evapo~~transpi~~ration values in the Deforestation run are, for most of the year, above control values, which explains the higher evapotranspiration during rainy season in comparison to Physiology scenario (although evapotranspiration is reduced in comparison to the control run, following the reduction in precipitation).~~close to the control values throughout the rainy season, which explains partly the comparatively moderate increase in temperature in this scenario~~

As shown, for example by Kooperman et al. (2018), the Physiological effects of eCO_2 on the region's climate take place namely in the wet season, when GPP is higher and transpiration is lower (see Fig. 6d and h), even though our results also show considerable rainfall reduction during the dry season. Conversely, it has been demonstrated (e.g. Lawrence & Vandecar 2015) that large-scale deforestation causes climatic changes namely during the dry season, when transpiration is particularly reduced, as also shown in our results (Fig. 6a and d).

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~~is related to higher water use efficiency (the amount of water used [in transpiration] per unit of carbon assimilated through photosynthesis), but even so ~~there~~ the net effect is a small decrease (~2%) of available soil water in the Physiology scenario, due to the ~~increase in temperature and evaporation~~decrease in precipitation. 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 GPP is considerably lower at this time of year in pasture grasslands~~coverage decreases from rainy to dry season, from a vegetation coverage fraction of 0.9 to 0.5~~, which, together with lower evapotranspiration and the decreased input of rainwater, act to decrease soil water in the dry season in the Deforestation scenario (Fig. ~~6e~~6f).

4. Discussion

Our results show that the modelled responses to eCO_2 and large-scale deforestation ~~lead to~~are associated with equivalent reductions of annual average precipitation and evapotranspiration in the Amazon region. The simulated decreases in precipitation (Physiology: 12%; Deforestation: 9~~13~~%) are ~~well~~ beyond Amazon region rainfall interannual variability of 5~~.1~~% (Spracklen and Garcia-Carreras, 2015). Different climatological mechanisms drive such reductions in the two scenarios. Both scenarios have in common ~~that the~~one 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 g_s of forest vegetation, whereas in the Deforestation scenario it is due to a ~~lower g_s, inherent to C4 photosynthetic pathway of tropical pasture grass,~~ a decreased ~~of~~ leaf area index~~, and a dry-season reduction in surface vegetation coverage~~. Another similar mechanism of change in both scenarios ~~is~~ the ~~strengthening~~ alteration of the Walker cell over the Amazon~~, ~~: in the Physiology scenario through a humidity-enriched free troposphere with decreased deep convection due to the heightening of a drier and warmer boundary layer in the Physiology scenario, and ~~with~~ in the Deforestation scenario through a strengthened moisture convergence in west/northwest Amazon and 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 near-surface atmospheric moisture content and 2m temperature over the Amazon region.

In fact the ~~enhancement~~ changes 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 driven namely by the lower surface roughness length. 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 winds (weakening of the Hadley Cell), which is apparently ~~due~~ linked to a combination of both a regional redistribution of convection and moisture converge/divergence, changes in the boundary layer depth and temperature, and, to a smaller extent, a teleconnection with eCO_2-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). The combination of eCO_2 and deforestation (see Figs. S1 to S4 in Supplement) result in patterns, for most of the variables, that are similar to those obtained in the Deforestation scenario, except for the spatial pattern of rainfall change which is less pronounced in west Amazon; and also for the circulation change pattern, in which the increase of easterlies in west Amazon is not as strong as in Deforestation, apparently due to the influence of eCO_2 on the atmospheric circulation over this region. 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~~S6), 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~~ is associated with~~to~~ a warmer (average of 1.9ºC [±1.8ºC] vs. -0.2ºC~~0.93~~ in the current simulation with CPTEC-BAM) and drier (average -15% vs. -~~13~~9% in CPTEC-BAM) climate over the region, driven namely by increase in trade-winds due to the considerably smaller roughness length of pastures (Lawrence and Vandecar, 2015; Sampaio et al., 2007; Spracklen and 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~~is combined with localized increase in rainfall, there is now modelling and observational evidence that widespread and large-scale deforestation in the Amazon drives rainfall reductions (Lawrence and Vandecar, 2015; 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 and Long, 2005; Aisworth and 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 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 18% reduction of g_s and 20% reduction of transpiration found in the Physiology scenario. However, water-use efficiency (calculated here as the ratio between G~~N~~PP 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~~94% in the Physiology scenario, owned to a stronger increase in G~~N~~PP in CPTEC-BAM (+13% in Oak Ridge FACE; +58~~75~~% in CPTEC-BAM). Although the temperature dependence of Rubisco kinetics imply that eCO_2 effects on GPP and NPP in the tropics should in principle be stronger (Hickler et al., 2008), ~~NPP~~ GPP 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~~12% ~~reduction~~ increase in the ~~NPP~~ GPP 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 eCO_2 in the Amazon forest~~. Additionally,~~, and 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. Additionally, multi-factorial ensemble simulation with gradual increase of CO_2 concentrations and of deforestation levels [*sensu* ~~(~~Sampaio et al., (2007)] could be valuable to understand when and how the effects of increasing CO_2 and deforestation dominate the rainfall responses in the Amazon region.

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~~ GPP and ~~stomatal conductance~~transpiration to eCO_2 in CPTEC-BAM, but also a consequence of the saturation of eCO_2 effects on ~~stomatal conductance~~g_s 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~~are associated with 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: 9~~13~~%) that are well above the interannual variability of precipitation in the Amazon of 5%. The two scenarios also ~~yield~~ show reductions in average annual evapotranspiration rates (Physiology or ß: -0.35~~3~~ mm d^{-1}; Deforestation: -0.~~29~~ 22 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~~ related to 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~~ related to ~~by the reduced stomatal conductance inherent to C^4 plants, smaller~~ the considerably lower leaf area index of pastures~~ and a dry-season decrease in surface vegetation coverage~~. In both scenarios there ~~is a strengthening~~are changes ~~of~~in the Walker circulation over tropical South America, with a convection zone concentrated over the Andes and a weak subsidence over east Amazon in the Deforestation scenario, and a reduction of deep convection, with high-troposphere subsidence anomalies in the Physiology scenario. 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 and is even ~~leads to~~associated with an increase of ~~atmospheric~~ specific humidity over the free troposphere profile~~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 is ultimately ~~leads to~~combined with 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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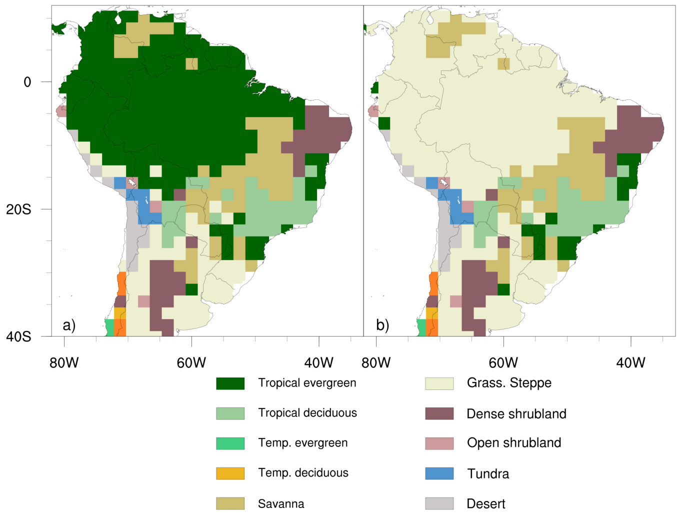

Figure 1: Vegetation maps used in (a) Physiology and (b) Deforestation modelling scenarios. Vegetation type grass. steppe in the Amazon region is composed of C^4 grass, representing tropical pasturelands.

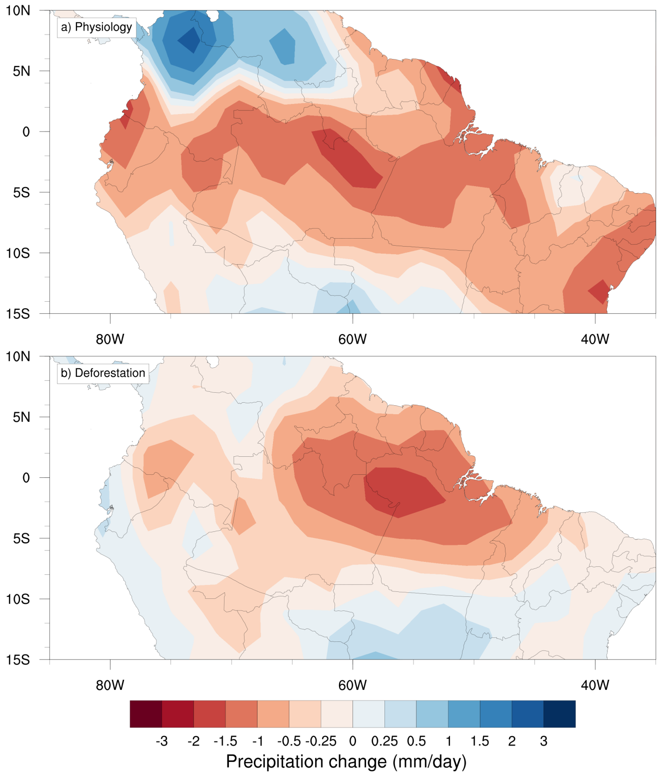

Figure 2: Annual mean precipitation change relative to control simulations using the CPTEC-BAM in tropical South America under (a) an atmospheric CO_2 concentration of +200 ppmv (1.5xCO_2) affecting solely surface vegetation physiology (Physiology), and (b) with complete substitution of the Amazon forest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

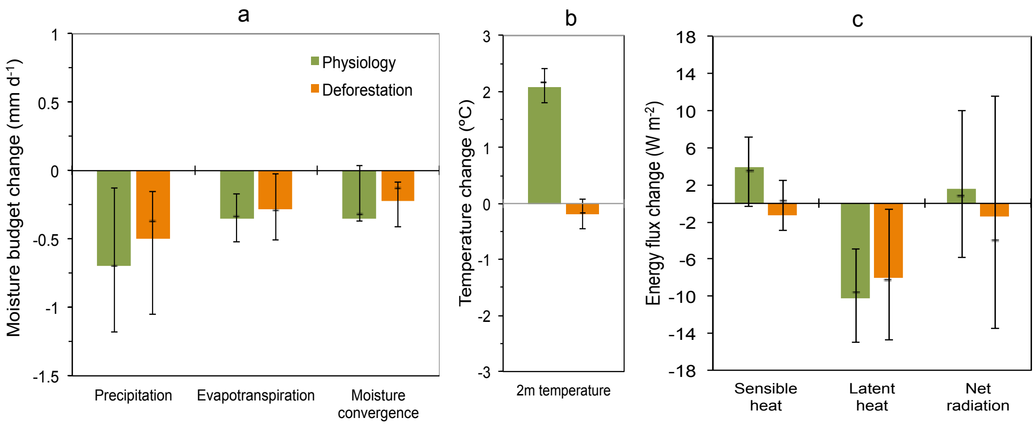

Figure 3: Mean annual changes in (a) moisture budget, (b) 2m-air temperature and (c) energy balance from the CPTEC-BAM over the Amazon region (black line square area in Fig. 5) under an atmospheric concentration of +200 ppmv (1.5xCO_2) affecting solely surface vegetation physiology (Physiology), and 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.

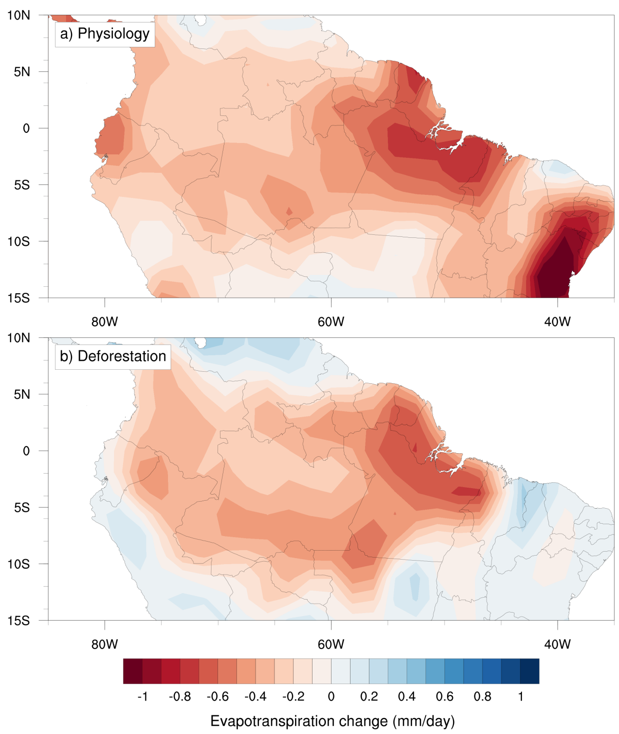

Figure 4: Annual mean changes in evapotranspiration in tropical South America (a) under an atmospheric concentration of +200 ppmv (1.5xCO_2) affecting solely surface vegetation physiology, and (b) with complete substitution of the Amazon forest by pasture grasslands.

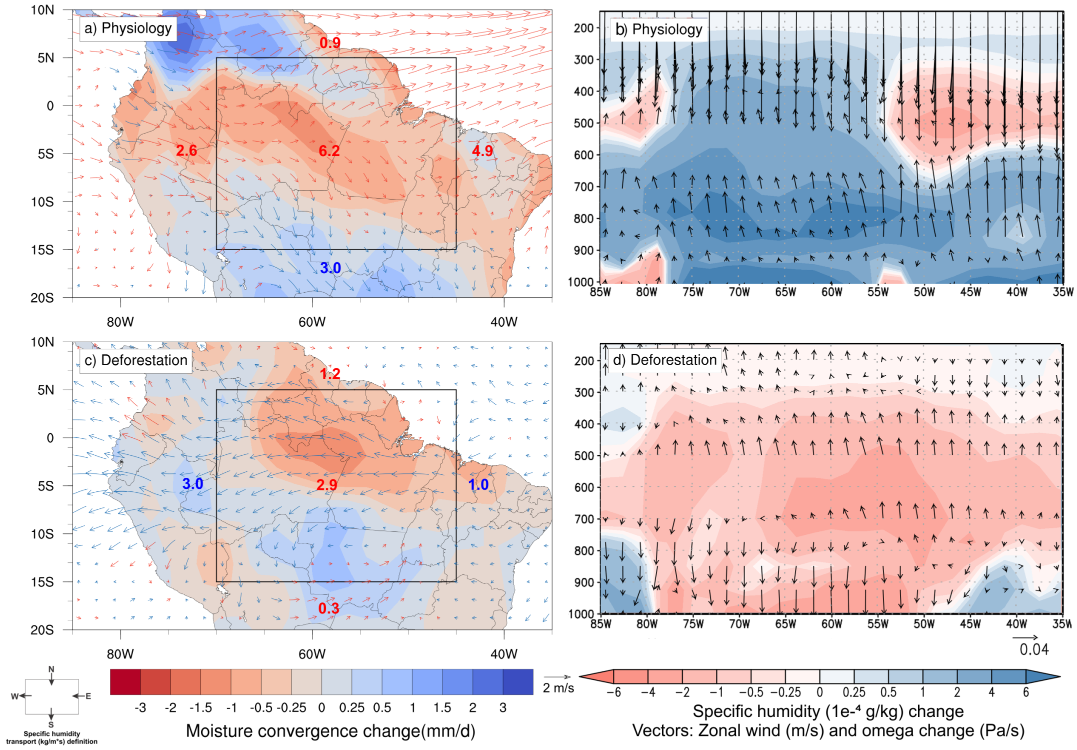

Figure 5: Annual mean changes in 850hPa horizontal wind (a, c) and vertical profile of zonal circulation over the equator superposed on meridional mean specific humidity vertical profile (with pressure in hPa as vertical coordinate) (b, d) in tropical South America under an atmospheric concentration of +200 ppmv (1.5xCO_2) (a, b) affecting ~~both~~ solely surface vegetation physiology, and (c, d) 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 500hPa) is calculated. Red and blue arrows/numbers represent respectively decrease and increase of the given variable.

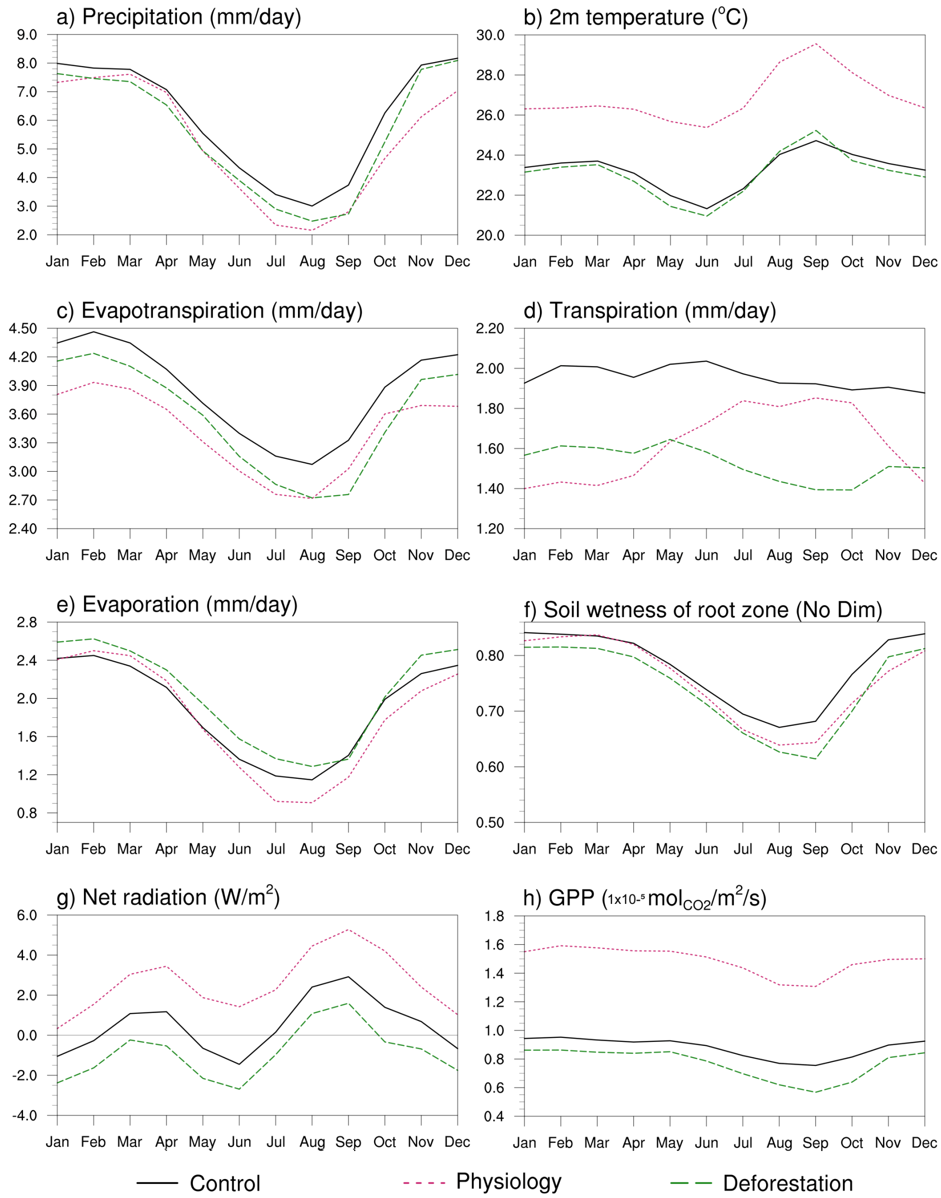

Figure 6: Mean monthly precipitation, 2m-temperature, evapotranspiration, transpiration, evaporation, topsoil water content, net radiation and gross primary productivity in the Amazon region (black line square area in Fig. 5) in the Control, Physiology and Deforestation modelling scenarios.

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
RCP8.5+Def**	Dynamic	588	588	Yes

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

** Results presented in Supplement.

Table 2: Mean annual changes and interquartile range (25th, 50th and 75th percentile values in parenthesis) of moisture budget, 2m-air temperature, energy balance, GPP, g_s and LAI from the CPTEC-BAM over the Amazon region (black line square area in Fig. 5) under an atmospheric concentration of +200 ppmv (1.5xCO2) affecting solely surface vegetation physiology (Physiology), with complete substitution of the Amazon forest by pasture grasslands (Deforestation).

Variable \ Scenario	Physiology	Deforestation
Precipitation (mm d^{-1})	-0.70 (-1.18; -0.70; -0.13)	-0.50 (-1.05; -0.37; -0.15)
Evapotranspiration (mm d^{-1})	-0.35 (-0.52; -0.33; -0.17)	-0.28 (-0.51; -0.29; -0.02)
Transpiration (mm d^{-1})	-0.35 (-0.53; -0.35; -0.19)	-0.42 (-0.66; -0.43; -0.19)
Moisture convergence (mm d^{-1})	-0.35 (-0.37; -0.32; +0.04)	-0.22 (-0.41; -0.13; -0.08)
2m temperature (ºC)	+2.07 (+1.80; +2.16; +2.40)	-0.20 (-0.45; -0.17; +0.08)
Sensible heat flux at surface (W m^{-2})	+3.96 (-0.32; +3.46; +7.17)	-1.34 (-2.91; +0.23; +2.44)
Latent heat flux at surface (W m^{-2})	-10.23 (-14.98; -9.60; -4.98)	-8.00 (-14.72; -8.27; -0.63)
Shortwave radiation at surface* (W m^{-2})	+1.94 (+0.59; +2.23;+3.90)	+3.88 (+3.91; +5.08; +3.88)
Longwave radiation at surface* (W m^{-2})	+2.75 (+2.24; +3.11; +3.85)	+6.9 (+4.84; +6.98; +9.26)
Net radiation (W m^{-2})	-1.58 (-9.16; -0.79; +6.63)	+1.36 (-8.88; +4.02;+16.17)
Cloud cover (%)	-1.4 (-2.1; -1.4; -0.6)	-2.2 (-2.9; -2.3; -1.7)
Gross primary productivity (μmolCO_2 m^{-2} s^{-1})	+7.0 (+5.0; +9.0; +9.0)	-1.0 (-2.0; -1.0; 0.0)
Stomatal conductance (molH_2O m^{-2} s^{-1})	-0.10 (-0.10; -0.07; -0.05)	-0.02 (-0.02; +0.001; +0.003)
Leaf area index	+10.0 (+7.0; +12.2; +13.2)	-4.1 (-5.5; -5.5; -2.7)

*Balance between incoming/absorbed and reflected/emitted radiation