Drivers and uncertainty of Amazon carbon sink long-term and interannual variability in CMIP6 models

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Abstract. The Amazon basin rainforest is a critical component of the climate system, currently representing 25% of terrestrial carbon gains and storing 150 to 200 billion tonnes of carbon. Whether the Amazon rainforest will remain a net carbon sink is an open scientific question: while its future stability and functioning may be compromised by climate change and anthropogenic pressures, Earth System Models (ESM) divergence in the projections undermines their reliability to simulate its future evolution. In this study, we examined the contribution of different climatic drivers behind the long-term and interannual variability evolution of the carbon sink within the Amazon basin using eleven CMIP6 ESMs, shedding light on the main factors contributing to inter-model diversity. By adopting the carbon-cycle feedback framework with C4MIP experiments, our results underscore the dominant role of CO_2 fertilization in driving long-term Amazon carbon sink trend and uncertainty. We also address the variability of carbon fluxes at the interannual timescale using a multivariate predictive model on historical and ssp585 ScenarioMIP simulations. With this respect, we emphasize the contribution of GPP modulation by shortwave incoming radiation as dominating NBP divergence across the ESMs ensemble. Additionally, we demonstrate that temperature-driven anomalies will be the main mechanism responsible for the higher Amazon carbon sink sensitivity to the El Nino Southern Oscillation (ENSO) under sustained global warming, predominantly as a result of the amplification of NBP sensitivity to temperature anomalies. Being the representation of terrestrial carbon cycle processes still one of the main uncertainties undermining ESMs projections, we therefore advocate for increased focus from modelling groups towards a more accurate and consistent representation of land processes and parameterizations, which will hopefully lead to reduced uncertainties in simulations coming from the next generation of ESMs.

1 Introduction

The Amazon basin rainforest plays a fundamental role in the climate system, serving as a prominent actor in the land carbon cycle and by exerting a significative influence on the global energy budget and hydrological cycle (Davidson *et al.*, 2012). At the same time, the land carbon sink represents one of the crucial uncertainties affecting climate change future evolution (Friedlingstein *et al.*, 2006; K. Arora *et al.*, 2020; Canadell *et al.*, 2021). Indeed, projections of the Amazon climate and carbon sink are still poorly constrained by state-of-the-art Earth System Models (ESMs), indicative of persisting gaps of knowledge regarding this critical aspect of the Earth system (Ahlström *et al.*, 2012; Zhu *et al.*, 2019; Xu *et al.*, 2020; Baker *et al.*, 2021; Koch, Hubau, *et al.*, 2021; Lin *et al.*, 2023; Raoult *et al.*, 2023).

The Amazon ecosystem has been a long-term carbon sink during the past decades contributing to approximately 25% of terrestrial carbon gains, estimated in 0.42-0.65 Gt C yr^{-1} for the period 1990–2007, a trend mainly driven since the 1980s by the CO_2 fertilization effect from rising CO_2 concentrations in the atmosphere (Phillips *et al.*, 2009; Pan *et al.*, 2011; O'Sullivan *et al.*, 2019; Walker *et al.*, 2021). Nevertheless, recent estimates have demonstrated a slow-down of net carbon sequestration and consequently a saturation and declining trend in the Amazon carbon sink, with increase in carbon losses due to drought events and increased temperatures (Brienen *et al.*, 2015; Hubau *et al.*, 2020). Both CO_2 concentrations in the atmosphere and climatic conditions affect land carbon fluxes. Higher atmospheric CO_2 concentrations exert mainly a positive direct effect on photosynthesis through plants stomatal closure and the associated negative Carbon-Concentration feedback (Boer and Arora, 2009; K. Arora *et al.*, 2020), while they can indirectly increase Ra and Rh (Gao *et al.*, 2020). Climatic conditions, on the other hand, mainly affect vegetation carbon fluxes through temperature and water availability, with, for example, negative temperature impacts on primary productivity and a positive (negative) relationship between temperature (water availability) and changes in respiration rates (Humphrey *et al.*, 2018; Gentine *et al.*, 2019; Green *et al.*, 2019; Liu *et al.*, 2020; Canadell *et al.*, 2021). With this respect, interannual variations of water availability and temperature in the Amazon basin are mainly related to El Niño-Southern Oscillation (ENSO), which is responsible for a vast part of the climatological and net land CO_2 fluxes variability observed in tropical biomes (Jones *et al.*, 2001; Kim *et al.*, 2016; Zhu *et al.*, 2017; Bastos *et al.*, 2018; Piao *et al.*, 2020; Mcphaden *et al.*, 2021a). Accordingly, some of the most severe droughts observed in the Amazon basin in recent decades and the associated reduction of the net land CO_2 sink were forced by strong ENSO events (or El Niños), most prominently the 1997/1998 and 2015/2016 ones (Jiménez-Muñoz *et al.*, 2016; Liu *et al.*, 2017; Koren *et al.*, 2018)**.** Despite indications of temperature-driven GPP anomalies were responsible for decreased Amazonian carbon sink in the 2015/2016 event (Bastos *et al.*, 2018; Zhang *et al.*, 2019), it is still currently debated whether fluctuations in temperatures or water availability are the dominant drivers for interannual carbon variability of tropical biomes, with recent research indicating the increased importance of water availability as a controlling factor in the past decades and with ESMs failing to reproduce this observed behavior (Jung *et al.*, 2017; Humphrey *et al.*, 2018; Liu *et al.*, 2023; Zhang *et al.*, 2023).

Consequently, at least three factors will contribute to determining whether, and to which extent, the Amazon ecosystem will remain a net carbon sink in the future decades under sustained positive radiative forcing: mean-state climatic changes, nutrient limitation, and ENSO modulation. First, a significant increase in surface air temperature and a marked decline in water availability in the Amazon basin deriving from increased greenhouse gas emission scenarios will most likely result in a less effective carbon sink by the end of the 21st century . In particular, coupled climate models suggest that the reduction in precipitation is driven by reduced evapotranspiration resulting from stomatal closure response to increased CO_2, which lead to changes in local surface energy balance and atmospheric circulation patterns (Kooperman *et al.*, 2018; Langenbrunner *et al.*, 2019; Li *et al.*, 2023; Kimm *et al.*, 2024). Then, Nitrogen and Phosphorous will likely limit tropical forests productivity (Fleischer *et al.*, 2019), an effect partly counterbalanced by the positive influence exerted by the increasing atmospheric CO_2 concentrations (Huntingford *et al.*, 2013; Koch, Brierley, *et al.*, 2021). Lastly, an increased Amazon vegetation sensitivity to ENSO is expected under a range of global warming scenarios (Kim *et al.*, 2017; Park *et al.*, 2020; Uribe *et al.*, 2023). In particular, global warming could affect the ENSO-Amazon teleconnection either from changes in mean-state and extremes in ENSO cycle, or from variations in the ENSO teleconnection mechanism itself (Chen *et al.*, 2017; Zheng *et al.*, 2017; Yeh *et al.*, 2018; Beobide-Arsuaga *et al.*, 2021; Cai *et al.*, 2021; Mcphaden *et al.*, 2021c). Notably, ENSO amplitude is slightly yet significantly enhanced under future global warming scenarios (Beobide-Arsuaga *et al.*, 2021; Cai *et al.*, 2022), and regional patterns of precipitation and temperature anomalies over South America associated with ENSO teleconnections are projected to be amplified in warmer climates (Perry *et al.*, 2020; McGregor *et al.*, 2022).

Given these premises, in this research we investigate the Amazon carbon sink using coupled simulations from CMIP6 ESMs simulations (Eyring *et al.*, 2016; O'Neill *et al.*, 2016) to separate the relative contributions of long-term changes and interannual variability under sustained atmospheric CO_2 concentrations and global warming. Specifically, throughout the paper, two question that remains underexplored in the literature are tackled: what are the relative contributions of inter-annual variability (IAV) and long-term climatic changes in the projected Amazon net carbon sink evolution? What is the role of ENSO in exerting a control on temperature and water availability? In doing that, an attempt is performed to identify the factors contributing to inter-model diversity in Amazon vegetation productivity projections across the ESMs considered.

2 Data and Methods

2.1 Data

We use simulations from eleven CMIP6 generation ESMs that contributed to both C4MIP and ScenarioMIP projects (Eyring *et al.*, 2016; Jones *et al.*, 2016; O'Neill *et al.*, 2016). In particular, the following experiments have been considered: 1pctCO2-bgc, 1pctCO2-rad, ssp585-bgc, ssp585-rad, historical and ssp585. Those ESMs for which at least one realization is available for all the simulation experiments and that have all the prognostic variables needed for the analysis available (or computable indirectly) have been included in the research. Table 1 presents an overview of the experiments considered and the methodologies adopted for each experiment. For the historical and ssp585 experiments, specifically, the first five realizations of each model (when more than one was available) were used to account for the uncertainty stemming from internal climatic variability, with the caution of having the same simulation members for the historical and ssp585 scenarios to make a pairwise comparison. The details of the ESMs used are reported in Table SI1. For these historical and ssp585 simulations, the analyses have been performed on single realizations, and aggregated by model solely for the graphical presentation of the results. The evolution of the land carbon-cycle is investigated by considering long-term changes and interannual variability of NBP values, which represent the balance of Gross Primary Productivity (GPP) due to photosynthesis at the net of autotrophic respiration (Ra), heterotrophic respiration (Rh) and disturbances, as fire dynamics (for those model having a fire module) and Land Use Change (LUC). Overall, the following variables have been considered in the study: sea-surface temperature (SST), Net Biome Productivity (NBP), Gross Primary Production (GPP), autotrophic respiration (Ra), heterotrophic respiration (Rh) , precipitation (Pr), soil moisture (mrso), air surface temperature (T) and shortwave incoming radiation (SWin).

Table 1: Overview of the experiments and methodologies used in the research. We refer to the work of Jones et al., **(2016)** and O'Neill et al., **(2016)** for more information on the C4MIP and ScenarioMIP experiments reported in this table.

Project	Experiments	Reference years	ESMs (n°)	Coupling	Effect estimated
C4MIP	1pctCO2-rad	36-150	11	Radiative-only	Long-term, Climate
	ssp585-rad	2015-2100	7	Radiative-only	Long-term, Climate
	1pctCO2-bgc	36-150	11	Biogeochemically-only	Long-term, CO_2 fertilization
	ssp585-bgc	2015-2100	7	Biogeochemically-only	Long-term, CO_2 fertilization
ScenarioMIP	historical	1750-2014	11	Coupled	Inter-annual variability (IAV)
	ssp585	2015-2100	11	Coupled	Inter-annual variability (IAV)

Zonal statistics computed within the Amazon basin and presented throughout the results are obtained by considering the grid-cells confined within the Amazon basin shapefile, available from the SO HYBAM service (INPE, 2019, https://hybam.obs-mip.fr/).

The ESMs performances in representing ENSO properties, the Amazon climatology, carbon and energy fluxes are evaluated against observational and quasi-observational products, and are reported in Figure S1-S4. HadISST dataset is used for assessing ESMs sea surface temperatures (Rayner *et al.*, 2003), while ERA5 and ERA5-Land products are used to validate temperature, precipitation and soil moisture (Hersbach *et al.*, 2020; Muñoz-Sabater *et al.*, 2021). Finally, the FLUXCOM-RS+METEO dataset, specifically the one forced with the WFDEI meteorological dataset (Weedon *et al.*, 2014), is used as a reference for both carbon fluxes (GPP, NEP, Total Ecosystem Respiration, TER) and energy fluxes (shortwave incoming radiation) (Jung *et al.*, 2019, 2020).

To evaluate ESMs against the reanalysis products, as well as to compute multi-model means across variables, a conservative remapping algorithm is applied to all the data to get a regular 1° longitude x 1° latitude grid, with the exception of SST from ESMs with a curvilinear grid (Table SI1), for which a distance weighted (nearest-neighbor) average remapping is applied. The validation procedure refers to the climatological period 1979-2013. When comparing the carbon fluxes from ESMs with FLUXCOM data, the total ecosystem respiration is obtained by summing the contributions of Ra and Rh. An overview of the ESMs evaluation performances is available in the supplementary material (Figures S1-S4).

2.2 Long-term mean-state climatic effects

Increasing trends of atmospheric CO2 concentrations affect terrestrial carbon sinks directly through a fertilization effect on vegetation (carbon-concentration feedback) and indirectly by forcing changes in the physical climate via a strengthened greenhouse effect, which in turn affects vegetation (carbon-climate feedback). A common approach to disentangle the two effect relies on the carbon-cycle feedback framework, by which it is possible to estimate the magnitude of the carbon-concentration feedback and the carbon-climate feedback (Jones *et al.*, 2016; K. Arora *et al.*, 2020). The contribution of these two feedbacks is estimated with the following linear equations:

$$\beta = \frac{\Delta NBP_{cum,BGC}}{\Delta ppm_{BGC}} \tag{1}$$

$$\gamma_T = \frac{\Delta NBP_{cum,RAD}}{\Delta T_{RAD}}; \quad \gamma_{mrso} = \frac{\Delta NBP_{cum,RAD}}{\Delta mrso_{RAD}}; \quad \gamma_{SW_{in}} = \frac{\Delta NBP_{cum,RAD}}{\Delta SWin_{RAD}} \tag{2}$$

Carbon sink is represented here by cumulative NBP, whose long-term sensitivity to CO_2 ppmv (β), and climate (γ), is estimated from biogeochemically only coupled simulations (1pctCO_2-bgc and ssp585-bgc) and radiative only coupled simulations (1pctCO_2-rad and ssp585-rad) respectively. Within the former, the increased CO_2 atmospheric concentration is uniquely exerting a biogeochemical effect which interests the terrestrial and ocean carbon cycle processes, whereas in the radiative simulation only the radiative transfer processes in the atmosphere are affected by the changing atmospheric CO_2 concentrations, with no consequences for biochemical processes (Friedlingstein *et al.*, 2006; Jones *et al.*, 2016). Changes are expressed with respect to the first year of the simulations; for 1pctCO_2 experiments only the years with atmospheric CO_2 ranges similar to the ssp585 scenario (400-1135 ppmv, resulting in 104 years) have been considered. On the other hand, the carbon-climate feedback has been further computed with respect to surface atmospheric temperatures (T), soil moisture (mrso) and shortwave incoming radiation (SWin), to represent the variety of mean-state climatic changes affecting the cumulative carbon fluxes within the Amazon basin.

2.3 Carbon fluxes sensitivity at inter-annual timescales

We further assessed the sensitivity of carbon fluxes within the Amazon basin at interannual timescales, to explore the short-term variability contribution of different climatic factors. With this respect, two additional analysis have been performed. A first one aimed at assessing the relative contribution of temperature, soil moisture and shortwave-incoming radiation on NBP, GPP, Ra and Rh by adopting a multivariate predictive regression model as in the following equation, for every ESMs considered:

$$\boldsymbol{\Delta NBP = \frac{\delta NBP}{\delta T} * \Delta T + \frac{\delta NBP}{\delta mrso} * \Delta mrso + \frac{\delta NBP}{\delta SW_{in}} * \Delta SW_{in} + \epsilon} \quad (3)$$

Temperature, soil moisture and shortwave incoming radiation have been chosen because of their primary control on carbon fluxes interannual variability (Jung *et al.*, 2017). We used soil-moisture rather than precipitation as a proxy for water availability due to its stronger control on terrestrial carbon fluxes (Humphrey *et al.*, 2018). We acknowledge that latent heat fluxes could partially contribute to interannual NBP variability by influencing vapor pressure deficit (VPD), which in turn affects NBP. However, we decided to exclude this factor from our framework (equation 3) because transpiration, which is regulated by stomatal conductance, impacts both NBP and latent heat fluxes, likely introducing correlation between them. All the variables considered have been averaged over the calendar year, as the focus of the analysis is on interannual variability. The dependent variable (NBP, as well as GPP, Ra and Rh) has been linearly detrended to remove the influence of CO_2 fertilization and other long-term climatic changes, while the three independent variables have been detrended and standardized (subtracting the mean and dividing by their standard deviation) to obtain comparable coefficients. Therefore, the standardized coefficients represent the quantitative contribution of temperature, soil-moisture and shortwave incoming radiation considering the simultaneous confounding impacts of the other variables. Specifically, a 5-fold cross-validation ridge regression model has been adopted, due to the penalty score in the cost function of ridge regression that helps to account for the collinearity among the predictors themselves. The cross-validation procedure entailed a randomized split of the dataset into training set (80%) and validation set (20%), and allowed for the selection of the best performing regularization parameter among a set of values spaced evenly on a log scale. The multivariate model derives from the Scikit-Learn package, available for the Python scripting language (Pedregosa *et al.*, 2012).

Given the predominant modulation of carbon fluxes IAV within the Amazon basin by means of ENSO (Mcphaden *et al.*, 2021a), a further analysis is conducted to assess the ENSO contribution to Amazon vegetation productivity mediated by either temperature and water-availability (using soil moisture as a proxy). For this, an annual time series of ENSO is obtained for each historical and ssp585 realization by averaging the corresponding monthly Nino3.4 index over the calendar year. The Nino3.4 index is defined as the 5-month moving average of mean sea-surface temperatures over the region 170-120°W and 5°S-5°N, subsequently detrended by means of a 1st order polynomial to remove the warming trend of SST. By taking the univariate sensitivities of temperature and soil-moisture to ENSO, and accounting for the partial derivatives of NBP with respect to temperature and soil-moisture as in Equation 3, we estimate the contribution of ENSO driven by the two mechanisms as below:

$$dNBP_{n34,T} = \frac{\delta NBP}{\delta T} * \frac{dT}{dn34} \quad (4)$$

$$dNBP_{n34,mrso} = \frac{\delta NBP}{\delta mrso} * \frac{dmrso}{dn34} \quad (5)$$

Using the partial derivatives $\frac{\delta \mathrm{NBP}}{\delta \mathrm{T}}$ and $\frac{\delta \mathrm{NBP}}{\delta \mathrm{mrso}}$ ensures that the effects of temperature and soil moisture are considered independently, accounting for potential confounding influences from each other, a condition not met if the univariate estimates $\frac{\mathrm{dNBP}}{\mathrm{dT}}$ and $\frac{\mathrm{dNBP}}{\mathrm{dmrso}}$ were applied. A Mann-Whitney U-test of independence with Bonferroni correction was used to assess whether the zonal values of the regression coefficients within the Amazon basin are significantly different between the historical period and ssp585 scenario. To mitigate the risk of overstating the significance of the statistical tests conducted, we employ a false discovery rate (FDR) control method based on (Wilks, 2016). This approach effectively addresses the issue of multiple hypothesis testing, ensuring a more accurate interpretation of the obtained results.

3 Results and Discussion

3.1 Intermodel uncertainties of carbon and climatic drivers

Amazon basin vegetation productivity and climatology shows substantial overlap across models during the historical period but strongly diverging trends across models during the ssp585 scenario, with individual models differing in magnitude and sign of projected changes (Figure 1a). The multi-model ensemble yields a cumulative NBP mean by the end of the 21st century of 59.3 ± 62 gCm^{-2}. Considering the projections of cumulative carbon sink in Figure 1a and carbon fluxes in Figure S5, the inter-model uncertainty is much higher compared to intra-model uncertainty (which stems from the intrinsic climatic variability expressed in each realization and is represented by the ±1 standard deviation spread in Figure 1 and Figure S5). For the physical variables in Figure 1b-e, intra-model uncertainty is considerably higher than for carbon fluxes and reflects the substantial internal climate variability intrinsic in each simulation. These considerations already highlight that part of the divergence across carbon cycle predictions is related to differences in the land sensitivity to climatic forcings, rather than uncertainties in the evolution of the climate itself. Overall, the climatological variables present a stronger agreement and coherence in the sign of projected changes among ESMs with respect to NBP. A multi-model mean reduction of -21.13 mm month^{-1}, -128.93 kgm^{-2} is projected for precipitation and soil moisture, respectively (Figure 1c,d), while an increase is observed for temperature and incoming shortwave radiation (+7.08 °C and +9.23 Wm^{-2}, respectively, Figure 1b,e). Still, the multi-model ensemble spread at the end of the 21st century remains substantial for all these variables. Differences among models of one or even two orders of magnitude could be seen for instance between MRI-ES2L and CanESM5 for shortwave incoming radiation or for MIROC-ES2L and IPSL-CM6A-LR regarding soil moisture projections.

For some models, divergent NBP projections cannot be easily attributed to similar deviations in the individual climatic drivers. For instance, ACCESS-ESM1-5 and NorESM2-LM projects similar end-of-the-century temperature and soil-moisture changes, but strongly diverging trends of cumulative NBP.

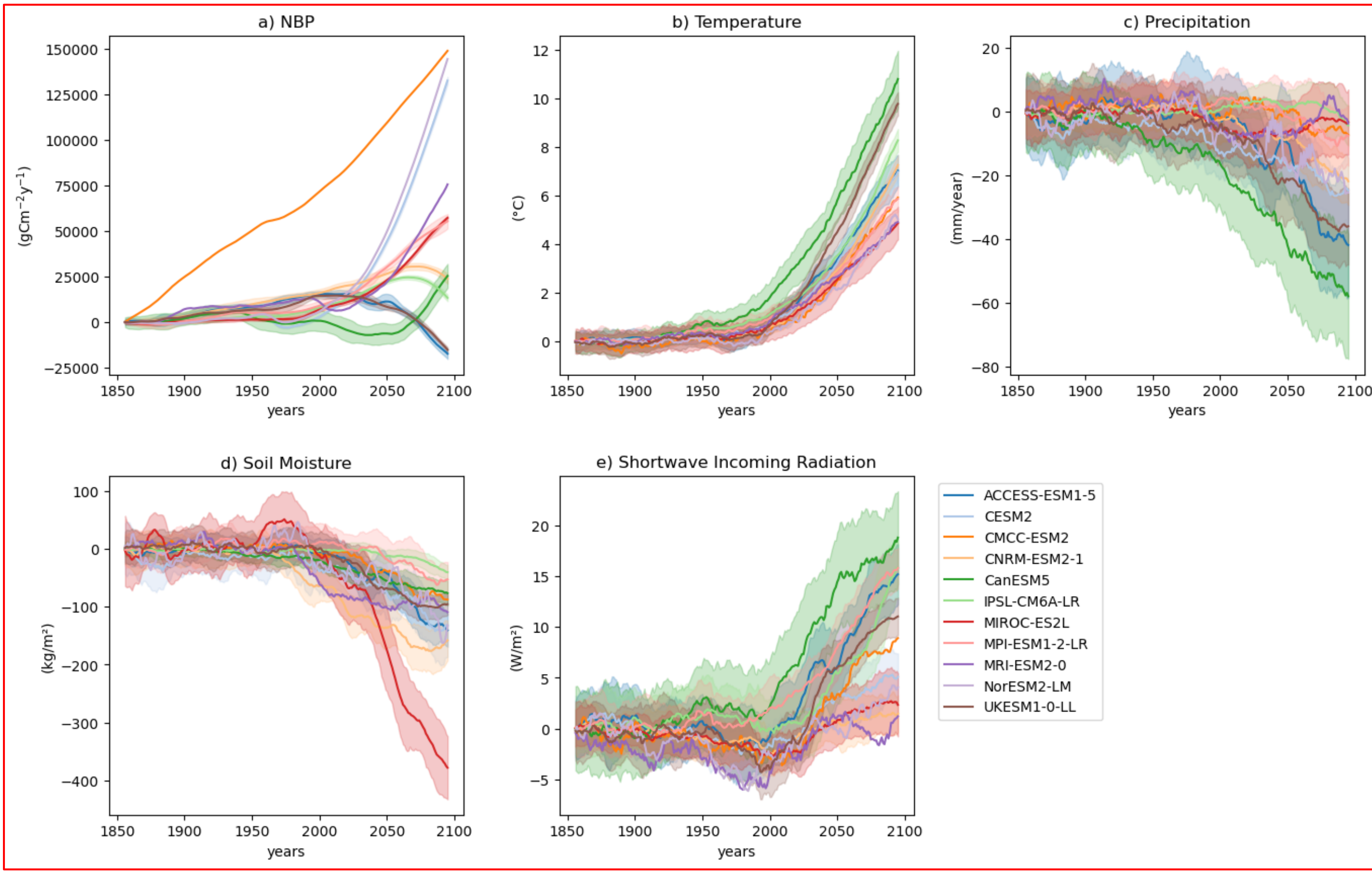

Figure 1: Long-term trends of (a) cumulative NBP, (b) temperature, (c) precipitation, (d) soil-moisture, (e) shortwave incoming radiation in the Amazon basin for the historical and ssp585 experiments. Trends are computed with respect to the first 30-year mean of the historical period (1850-1880), and are visualized as a 10-year moving average for clarity. For the models with more than one realization, both the model-ensemble mean (line) and the spread (±1 standard deviation, shading) are shown.

Regarding the intra-model spread, the highest influence of internal climatic variability (±1 standard deviations) is observed in precipitation and shortwave incoming radiation, followed by soil-moisture (spreads in Figure 1c,e and d). This indicates that within the Amazon basin, the major source of uncertainty deriving from internal climate variability is associated with cloud formation and coverage, which is causally linked with the amount of precipitation (thus soil moisture content) and shortwave incoming radiation within the regional domain. All the carbon fluxes from which NBP is derived (GPP, Ra and Rh) depict an increasing trend throughout the 21^{st} century (Figure S5), with the notable exception of GPP and heterotrophic respiration for

ACCESS-ESM1-5. Among these carbon fluxes, Rh presents the highest end of 21st century normalized uncertainty (186.74 gCm^{-2}, z-score std-dev of 1.62), followed by GPP and Ra (753.59 and 548.71 gCm^{-2}, z-score std-dev of 1.12 and 0.76 respectively). This shows that uncertainty in cumulative NBP does not solely stem from uncertainty in single climatic factors; instead, it arises from inconsistencies and differences in how models represent photosynthetic activity, autotrophic and heterotrophic respiration. Overall, inconsistencies in projected Amazon NBP cannot be simply understood as a consequence of discrepancies in the climatic factors affecting vegetation, as discussed already by Heavens et al., (2013) . A point that deserves attention is therefore how the projected carbon sink in the Amazon basin is sensitive to mean-state changes in environmental drivers and climatic variability at the interannual timescale.

3.2 Long-term carbon sink sensitivity

By applying the carbon-cycle feedback framework (see Methods), the net carbon sink (cumulative NBP) response is explained by the factor β (CO_2 fertilization) and by the factor γ (climate effect). The net carbon sink trend driven uniquely by the CO_2 fertilization effect and climate is reported in Figure S6a and Figure S6b, respectively, where the consistent agreement across ESMs on the direction of the projected land carbon response to these two factors is evident.. The spatial magnitude of β derived from the 1pctCO_2-bgc simulation is showed in Figure S7. Most of the ESMs project a strong CO_2 fertilization effect within the Amazon basin for the range of atmospheric CO_2 concentrations of the ssp585 scenario, despite considerable variability could be observed across the models. CESM2 and NorESM2-LM present the higher vegetation sensitivity to atmospheric CO_2, reasonably due to the fact that both the models share the same land module CLM5 (Table S1). CMCC-ESM2 also presents high β values, but these are restricted to the most forest-dense pixel cells, as it is clear from the sharp decline in the southern and south-eastern part of the basin, a pattern which is even more drastic in ACCESS-ESM1-5.

Despite the carbon cycle feedback framework entails to describe the positive carbon-climate feedback considering surface air temperature, the values of the standardized γ_{tas}, γ_{mrso} and γ_{rsds} are reported in Figure S8 with the purpose of providing a quantitative comparison of the ESMs sensitivity to diverse climatic factors. Therefore, γ_{tas}, γ_{mrso} and γ_{rsds} are not to be intended as cumulative long-term impact coefficients. Remarkable negative effects on Amazon carbon sink are associated with long-term increasing temperatures, and partially with less intensity, with rising trends in shortwave incoming radiation. The positive co-variability of the carbon sink with soil-moisture is almost specular of the cumulative NBP sensitivity to shortwave incoming radiation, a consequence of the strong inverse correlation among the two factors, reflecting a reduction of cloud coverage and precipitation in the Amazon basin with increasing atmospheric CO_2 and climate warming.

Consequently, the long-term cumulative NBP for the 1pctCO_2 scenario is reconstructed by means of its sensitivity to mean-state changes of temperature and atmospheric CO_2 and is reported in Figure 2. These results emphasize that CO_2 fertilization effects on vegetation productivity are expected to dominate and overcome the negative temperature influence on the long-term carbon sink evolution in the ssp585 scenario.

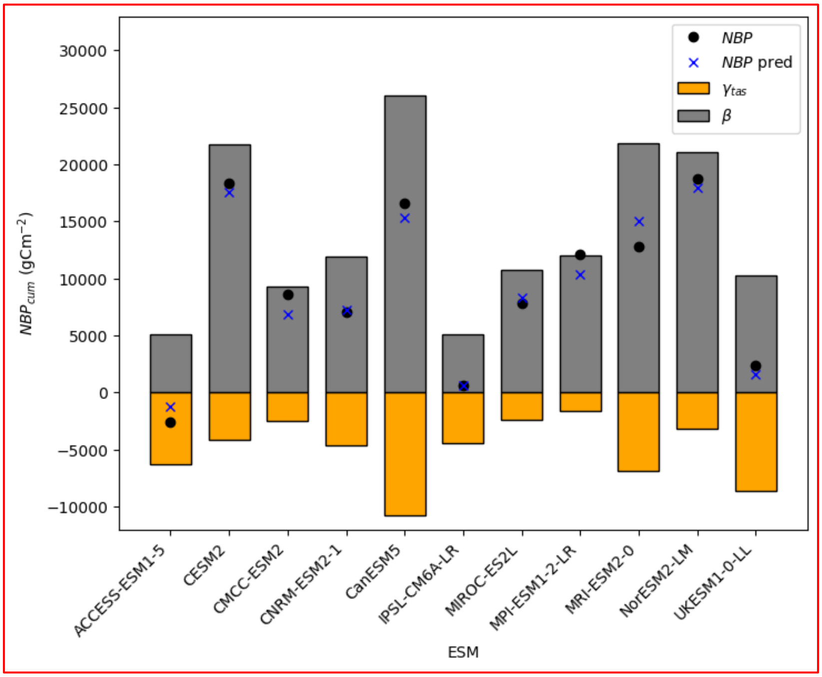

Figure 2: Contribution of carbon-concentration (β) and carbon-climate feedbacks (γ_{tas}) to net carbon sink projections at the end of the 1pctCO2-bgc and 1pctCO2-rad simulations. Black dots represent the net cumulative NBP resulting from the arithmetic sum of cumulative NBP from 1pctCO_2-bgc and 1pctCO_2-rad simulations, whereas the blue crosses are the result of the arithmetic sum of the estimated cumulative NBP by adopting the univariate β and γ_{tas} coefficients. Values are averaged within the Amazon basin domain.

Regarding the differences across ESMs, these discrepancies in the long-term climate-driven trend of net carbon sink in the Amazon region emerge from a very strong correlation between its sensitivity to soil-moisture γ_{mrso} and temperature γ_{tas}, as reported in Figure 3 and Figure S9 for both 1pctCO2-rad and ssp585-rad simulations. Therefore, the Amazon carbon sensitivity to long-term climatic changes is not only discernible in the negative temperature effect, but it is also found in the positive influence to soil-moisture, indicating that the land modules of the ESMs are similarly sensitive to both the factors, despite with an inverse relationship. Additionally, temperature emerges as playing a slightly stronger role in describing the variations of carbon sink response across the different ESMs compared to soil moisture (R^2 coefficient of 0.85 vs 0.71, as illustrated in Figure 3a and Figure 3b).

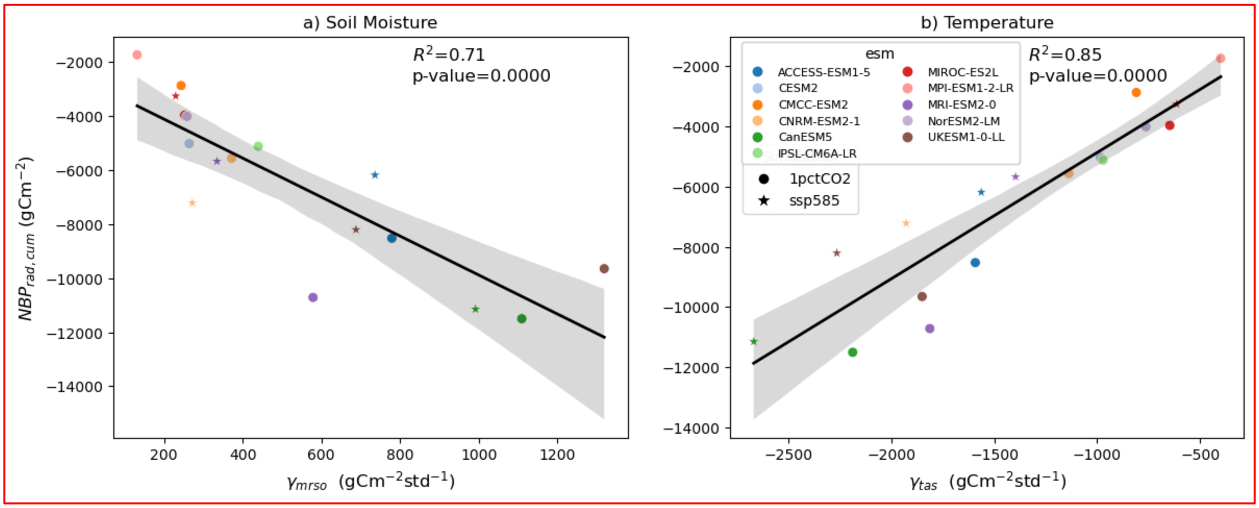

Figure 3: Intermodel uncertainty in climate-driven cumulative NBP (y-axis) as explained by differences in ESMs representation of temperature (**γ_{tas}**) and soil moisture (**γ_{mrso}**) impacts in 1pctCO2-rad and ssp585-rad simulations. The reported values are the zonally averaged within the Amazon basin geographical domain.

3.3 Inter-annual variability of carbon fluxes

Amazon carbon sink variability on shorter (interannual) timescales is assessed for the historical and ssp585 scenario considering the modulation of temperature, soil moisture and shortwave incoming radiation anomalies using a multi-linear ridge regression predictive model (see Methods). The skills of the model optimized with the 5-fold cross-validation procedure are reported in Figure S10. Overall, a multi-model mean coefficient of determination of 0.55 is obtained, despite with substantial differences across ESMs. Remarkably lower values of variance explained (R^2<0.4) are found for CESM2, CMCC-ESM2 and NorESM2-LM, whereas CanESM5, MIROC-ES2L and UKESM1-0-LL stand out as the models with the highest goodness of fit and predictive capability (R^2>0.6) (Figure S10a). Undoubtedly, we acknowledge the limitations that arise from the adoption of a linear ridge regression model. As we didn't account for interactive and non-linear effects among the predictors influencing NBP IAV, we are not able to capture a portion of the unexplained variance in our regression model. The results in Figure S10 reflects this fact, suggesting that other factors, as well as the effects emerging from the interaction of temperature, soil-moisture and shortwave incoming radiation, are likely having an important influence on NBP IAV, especially for CESM2, NorESM2-LM and partly CMCC-ESM2. Nevertheless, we opted for this modelling framework, as it still allows our results to be compared with prior works (Jung *et al.*, 2017; Humphrey *et al.*, 2018).

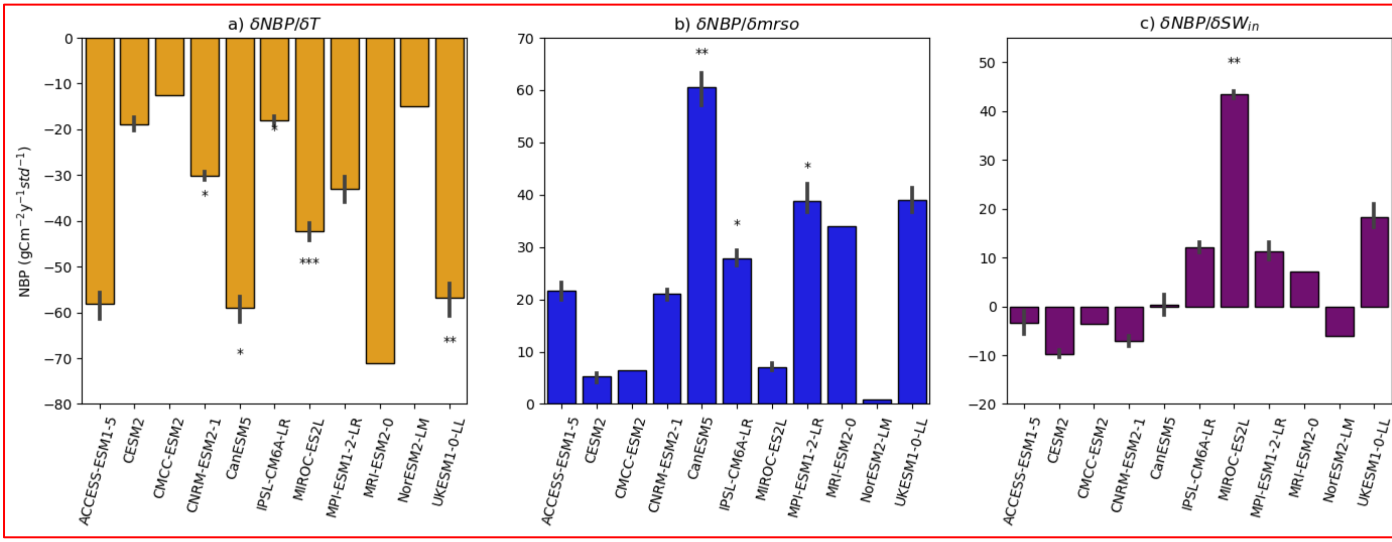

Figure 4: Partial derivatives explaining the contribution of temperature (a), soil moisture (b) and shortwave incoming radiation (c) to interannual NBP, averaged across the Amazon basin. The black vertical bars represent the spread in the predictors coefficients for models with more than one realization available, whereas the stars indicate the level of significance (p-value), averaged over the Amazon basin, associated to every coefficient. Statistical significance refers to the following convention: *: 1.00e-02 < p <= 5.00e-02; **: 1.00e-03 < p <= 1.00e-02; ***: 1.00e-04 < p <= 1.00e-03; ****: p <= 1.00e-04

The relative importance of the three variables in explaining the NBP interannual variability is reported in Figure S11 for both the historical period (panel a) and the ssp585 scenario (panel b), revealing the dominant regulation of temperature for all the ESMs except CanESM5, IPSL-CM6A-LR and MPI-ESM1-2-LR, that have primarily a soil-moisture driven variability and MIROC-ES2L, which stands out for the particularly high variance explained by shortwave incoming radiation and the low contribution of soil-moisture. As will be discussed later in the next section, temperature modulation is expected to be particularly predominant in the ssp585 scenario (Figure S11b), intensified by climate change. Similar consideration can be drown by observing the standardized coefficients estimated for NBP. Those, reported for the ssp585 scenario in Figure 4, point to an intermodel qualitative agreement with respect to the contribution of temperature (negative effect) and soil-moisture (positive effect), despite with remarkable differences in the magnitude of the drivers contribution. Lower net carbon sink variability, on the other hand, is associated with shortwave incoming radiation, with ESMs diverging on the sign of the partial derivative (Figure 4c).

Similar results are found for the multilinear regression estimation in the historical period: compared to this, a general increase in the sensitivity is found for temperature and soil moisture effects in the ssp585 scenario (Figure S12), mainly a consequence of increased future interannual NBP variability. In Figure 4, seven out of eleven models project temperature as the first NBP predictor, while for CanESM5, IPSL-CM6A-LR and MPI-ESM1-2-LR soil moisture results to be more important, and MIROC-ES2L predicts shortwave incoming radiation as the most dominant driver of NBP IAV. Overall, these results complement and partially confirm what shown in a recent research (Padrón *et al.*, 2022), which found temperature to be more important than soil moisture to explain interannual variability of NBP in an ensemble of models, considering the ssp126 low emission scenario.

The spatially explicit multi-model ensemble coefficients for NBP are reported in Figure 5, with hatches delimiting those pixel cells where eight out of eleven ESMs agree in the sign of the partial derivative. Temperature impacts are particularly evident in the northern part of the Amazon, whereas the positive influence of soil moisture presents high agreement almost everywhere with the exception of the north western part of the basin. Considering the almost specular multi-model agreement in the positive value of shortwave incoming radiation coefficients in that specific domain, this could reflect that the majority of the ESMs present an energy limited regime in the area, with shortwave incoming radiation (rather than water availability) being the main limiting factor constraining ecosystem productivity at interannual timescales.

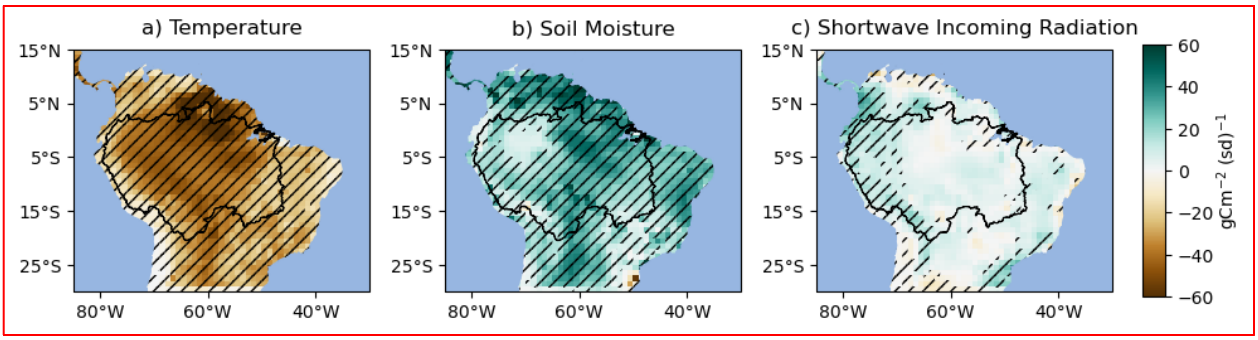

Figure 5: Multi model ensemble mean of the coefficient values for the climatic drivers obtained by the multi-linear regression, for the ssp585 scenario. Hatches represent those grid cells for which at least 8 out of 11 ESMs agree in the sign of the predictor value. The Amazon basin, obtained from the SO HYBAM service (https://hybam.obs-mip.fr/), is also represented.

As observed for long-term effects in Figure 3, the intermodel differences in the projection of net carbon sink variability at interannual timescales are characterized by an inverse relationship between temperature and soil moisture influence: high NBP interannual variability (expressed as NBP standard deviation, y-axis in the panels of Figure S13) is driven by lower temperature (Figure S13a) and higher soil moisture contributions (Figure S13b).

We then identify the physical processes associated with net carbon sink that exhibits the greatest uncertainty by analysing the variability in the estimated coefficients for each dependent variable (NBP, GPP, Ra and Rh), reported in Table 2.

In this procedure, the coefficients obtained from the multivariate regression model have been further standardized by dividing each coefficient by the standard deviation of its corresponding dependent variable, ensuring a fair comparison both across models and for the different dependent variables.

Table 2: Inter-model uncertainty within the Amazon basin, expressed as std.dev. of the partial derivative values across all the ESMs. Rows represent the partial derivatives of temperature, soil moisture and shortwave incoming radiation, with respect to the dependent variables reported in the columns (carbon fluxes).

	NBP	**GPP**	**Ra**	**Rh**
$\frac{\delta Carbon}{\delta T}$	0.14	0.15	0.34	0.42
$\frac{\delta Carbon}{\delta mrso}$	0.24	0.25	0.31	0.45
$\frac{\delta Carbon}{\delta SW_{in}}$	0.28	0.36	0.30	0.30

The high disagreement in the sign of the shortwave incoming radiation coefficients found for NBP (panel c in Figure 4) originates from GPP sensitivity to shortwave incoming radiation $\frac{\delta GPP}{\delta SW_{in}}$ (Figure S14). Uncertainties in net carbon sink projections across ESMs therefore arise, on the one hand, mainly from differences in photosynthesis modulation by light availability. On the other hand, heterotrophic respiration sensitivity to soil moisture and temperature represents another prominent source of uncertainty across ESMs (see also panel a, b in Figure S15 showing the disagreement across ESMs coefficients), whereas autotrophic respiration shows median contributions to net carbon sink uncertainty (Table 2 and Figure S16).

3.4 ENSO modulation

Given the predominant role of large-scale climatic modes of variability in influencing local climate and carbon cycle, the NBP response to ENSO has been investigated. ENSO is the most important climatic mode affecting and modulating net tropical carbon sink variability at interannual timescales, and changes in key properties of ENSO could significantly impact the Amazon basin region. For example, an increase in the frequency or in the magnitude of El Niño and La Niña events under global warming, a possibility explored in previous studies (Cai *et al.*, 2014, 2015; Berner *et al.*, 2020; Brown *et al.*, 2020; Fredriksen *et al.*, 2020), could have important implications especially for the Amazon ecosystem due to a stronger inhibition of the boreal winter southward shift of Inter Tropical Convergence Zone (ITCZ) that regulates the ENSO tropical teleconnection pathway. Another ENSO property that could influence the Amazon carbon cycle is the spatial location of SST anomalies in the tropical Pacific, resulting in the distinction between Central Pacific (CP) and the Eastern Pacific (EP) ENSO events (Mcphaden *et al.*, 2021b). This spatial diversity in ENSO have been shown to have different impacts on GPP and NEP in many regions of the world, especially in the Amazon basin (Dannenberg *et al.*, 2021), and some studies have also shown that CP El Niños are projected to be more frequent under 21st century warming (e.g., Shin et al., 2022). However, the consideration of these ENSO properties lie outside the domain and the purpose of the present research, and we leave it for future studies.

The ESMs in the considered ensemble largely overestimate the observed ENSO amplitude in the interannual-to-decadal band, with the associated spectra typically featuring a narrow peak around the 3-year periodicity (Figure S17). The ESMs also yield a diversity of changes in ENSO spectral characteristics under the warming scenario: generally, all the models represents a shift of ENSO signal toward higher frequencies, with weaker amplitude at decadal time scales and stronger amplitude at interannual time scales (Figure S17). Changes in the amplitude of the ENSO signal, represented by the Nino3.4 index standard deviation, between the ssp585 scenario (orange dots) and the historical period (light-green dots) are shown in Figure S18. Nine out of eleven ESMs show an increased ENSO variability under the ssp585 scenario, whereas CESM2 do not project any relevant changes, and UKESM1-0-LL predicts a slight decrease in ENSO amplitude.

We estimate the NBP variability related to ENSO by considering both the sensitivity of NBP to temperature and soil moisture, as well as the sensitivity of temperature and soil moisture to the Nino3.4 signal (see Methods), thus allowing to decompose the impacts associated to the two different mechanisms. The results are showed in Figure 6. First, all the models represent larger carbon sink losses related to temperature-driven anomalies compared to soil moisture ones. Second, temperature and soil moisture impacts driven by ENSO are expected to increase in magnitude during the future ssp585 scenario compared to the historical period, with the increase in $\delta NBP_{n34,T}$ appearing to be statistically significant for all the models but MPI-ESM1-2-LR and NorESM2-LM. Regarding $\delta NBP_{n34,mrso}$, on the contrary, most of the ESMs (seven out of eleven) project either a not-significant change, or a relatively low statistical significance (0.05<p-value<0.01). While the carbon cycle response to ENSO within the Amazon region presented here is well in agreement with previous research (Kim *et al.*, 2017; Betts *et al.*, 2020; Le *et al.*, 2021; Le, 2023), our results further identify temperature as the key factor in the mechanism by which ENSO affects Amazon carbon fluxes in a high radiative forcing future scenario. Specifically, the higher temperature-mediated ENSO impacts arise from the higher (lower) co-variability observed in the ESMs between temperature (soil moisture) anomalies and ENSO, both during the historical period as well as in ssp585 projections (Figure S19). This is accentuated by the stronger response of NBP to temperature changes compared to soil moisture for the majority of ESMs, as mentioned above in Figure 4.

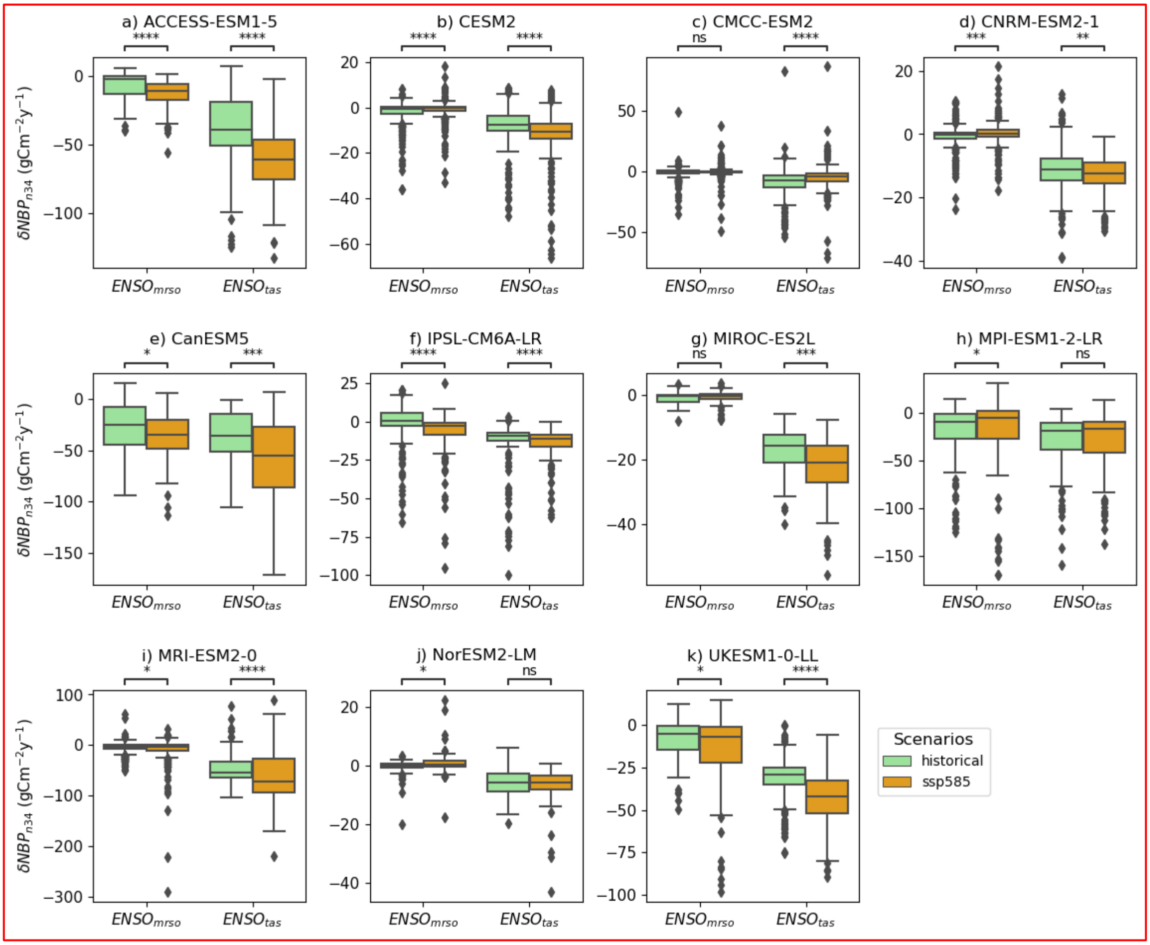

Figure 6: Variability of NBP at interannual timescales associated to ENSO (y-axis), and mediated by either soil moisture or surface air temperature (x-axis), for every ESM. Reported are the distribution of the values within the Amazon basin, for the historical period (light-green) and the ssp585 scenario (orange). Statistical difference among the distribution of the coefficients for the two periods are tested by means of a Mann-Whitney U-test and is reported in the stars above the plots with the following convention: *: 1.00e-02 < p <= 5.00e-02; **: 1.00e-03 < p <= 1.00e-02; ***: 1.00e-04 < p <= 1.00e-03; ****: p <= 1.00e-04.

The influence of ENSO by means of temperature and soil moisture anomalies is additionally examined considering the multi-model ensemble mean of $\delta NBP_{n34,T}$ and $\delta NBP_{n34,mrso}$. To do so, the ESMs coefficients reported in Figure 4 have been re-gridded to a common 1x1 grid using bilinear interpolation. As discernible from Figure 7, the temperature-driven impacts of ENSO are expected to be clearly stronger in the future ssp585 scenario compared to the historical period (panel a), as well as with respect to soil moisture driven impacts (panel b). Considering that climatic variability associated to ENSO in the Amazon basin in not expected to significantly change in the ssp585 scenario with respect to the historical simulation for all the models (Figure S19), these results indicate that climate change will significantly amplify the NBP sensitivity to temperature anomalies in the Amazon, while its influence on NBP sensitivity to soil moisture anomalies will be less pronounced.

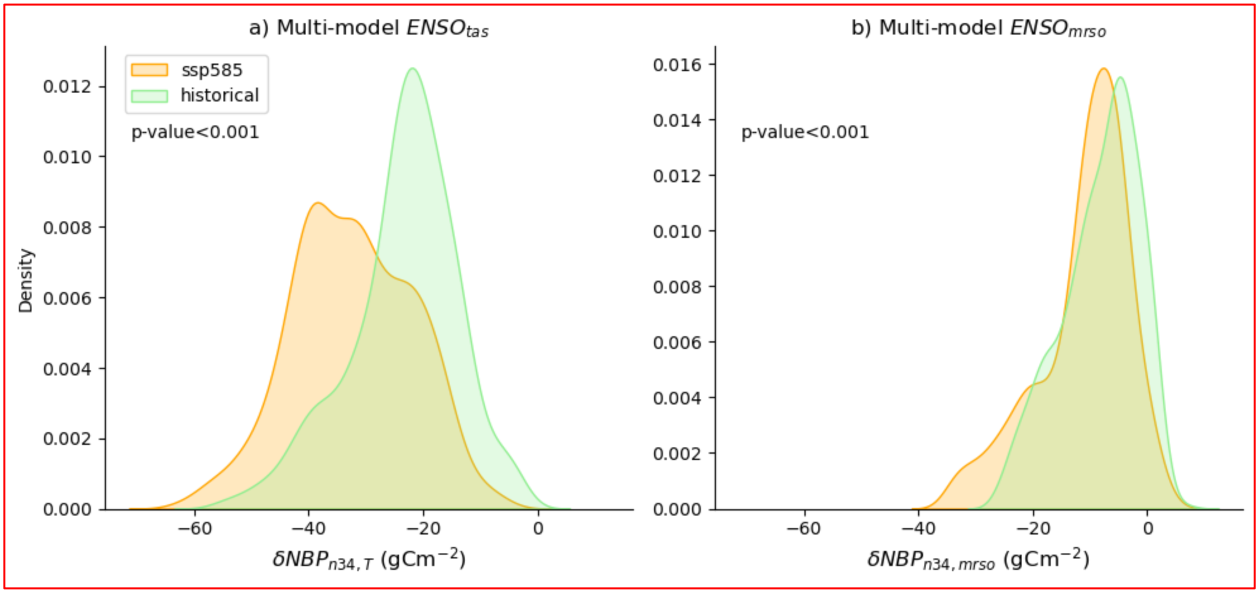

Figure 7: Only grid-cells within the Amazon basin are included. Statistical significance, tested by means of a Mann-Whitney U-test, is reported in the stars above the plot, and refers to the following convention: *: 1.00e-02 < p <= 5.00e-02; **: 1.00e-03 < p <= 1.00e-02; ***: 1.00e-04 < p <= 1.00e-03; ****: p <= 1.00e-04

4 Conclusions

In conclusion, in this study we assessed the main environmental drivers affecting the long-term and IAV projections of Amazon basin carbon sink under the ssp585 high radiative forcing scenario with respect to eleven CMIP6 ESMs. Several important outcomes have been identified and confirmed.

Specifically, we recognised CO_2 fertilization as the predominant mechanism determining the long-term Amazon carbon sink trend and uncertainty under the range of atmospheric CO_2 concentrations of the ssp585 scenario (400-1135 ppmv). These results reaffirm, for the CMIP6 generation of ESMs, what reported in a previous study by Huntzinger et al. (2017), that under different research assumptions showed the predominant role of vegetation sensitivity to CO_2 in shaping the net carbon sink variability across CMIP5 generation Land Surface Models (LSMs). Additionally, we disentangled the fundamental physical processes behind net carbon sink discrepancies across ESMs, highlighting dominant mechanisms affecting simulated carbon fluxes uncertainty for the Amazon basin ecosystem. Particularly, we show that the ensemble divergence of NBP under future warming scenario is largely determined by GPP modulation by shortwave incoming radiation and uncertainty in the representation of heterotrophic respiration sensitivity to both soil moisture and temperature. Our multi-model ensemble approach expands the results obtained in previous researches (Ma *et al.*, 2021) by allowing for an explicit consideration of model uncertainty. By showing the strong uncertainties across the driving factors of heterotrophic respiration, we suggest that not only ESMs differ in the positive modulation of temperature on Rh (controlled by the Q_{10} equation), but also largely disagree in the association between soil moisture and soil decomposition rates leading to respiration fluxes, as recently pointed out by Guenet et al., (2024).

Additionally, our results point towards a stronger ENSO-driven temperature impact on carbon sink anomalies for the vast majority of ESMs, compared to the effects associated with deficits in water availability. Accordingly, the CMIP6 multi-model ensemble considered shows a robust and statistically significant increase in carbon sink sensitivity to ENSO-driven temperature anomalies under global warming in the region of the Amazon basin: as a consequence, climate change is likely to significantly diminish the Amazon ecosystem capacity to function as a carbon sink, further aggravating the atmospheric CO_2 burden. This outcome highlights the critical role that global warming induced changes in the dynamics of modes of interannual variability could have on the Amazon region, thus contributing to the expanding scientific literature on the topic (see for example Le, 2023; Yan *et al.*, 2023). Overall, despite we were able to, at least partially, understand and quantify the contributions of different driving factors in affecting Amazon carbon cycle projections, important uncertainties still remain in the projections of Amazon response to global warming in CMIP6 generation of ESMs. On another note, we acknowledge some limitations affecting our study, particularly the application of a linear framework to describe interannual variability of carbon fluxes and ENSO-mediated impacts. A potential approach to overcome this limitation could be the adoption of machine-learning algorithms, able to detect non-linearities and describe the complex spatio-temporal features of the Earth system (Reichstein *et al.*, 2019). This, together with a more up-to-date and uniform representation of vegetation physiological and biogeochemical processes in the next generation of ESMs, will hopefully help generate more coherent and reliable projections of terrestrial carbon fluxes, helping to understand the faith of the Amazon basin under global warming scenarios.

Code availability: The code used to perform the analysis is publicly available at https://github.com/Matteo-Mastro/Amazon_CMIP6

Data availability: CMIP6 data are freely available and accessible from the ESGF repository (https://aims2.llnl.gov/search). FLUXCOM energy and carbon fluxes data are accessible from the Data Portal of the Max Planck Institute for Biogeochemistry, previous registration (https://www.bgc-jena.mpg.de/geodb/projects/Home.php). HadISST dataset is freely accessible from the MetOffice website (https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html). ERA5 and ERA5-Land data are freely accessible from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/#!/home). The Amazon shapefile used for computing the spatial mean statistics is freely available from the Amazon basin water resources observation service (https://hybam.obs-mip.fr/).

Author contribution: MM designed the study with contributions and feedbacks from DZ and DP. MM developed the model code and performed the analysis. MM prepared the manuscript with contributions and feedbacks from all the co-authors.

Competing interests: The authors declare that they have no conflict of interest.

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