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A changing Amazon rainforest: historical trends and future projections under post-Paris climate scenarios

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Abstract. Despite the progress in sustainable development strategies, the role of the Amazon rainforest as a carbon sink faces increasing disturbances that may have a critical impact on global climate. Understanding the vulnerability of the Amazon rainforest to climate change is a major challenge, considering the complex interaction between human and natural systems. This paper aims, via an interdisciplinary approach, to assess the observed evolution and possible future of the Amazon rainforest, considering different global climate and socio-economic scenarios. By comparing historical with plausible future developments, we present key knowledge to inform mitigation and regional adaptation policy considerations. As an entry point, historical trends of annual mean temperature and precipitation were analysed. In a second step, the same assessment was made for the mean annual NDVI sum (a proxy of yearly plant productivity), representing vegetation strength. For these purposes, a 34-year period (1982-2015) was considered. Trends were analysed based on non-parametric Mann-Kendall and Sen's methods. With this representation of the past, the next step focused on future scenarios. The most plausible global emission pathways were evaluated via the comparison of ten assessments of the possible effects of the mitigation action plans of national governments, as stated in the National Determined Contributions (NDCs). Results indicate a strong consensus that if either current policies, unconditional or conditional NDCs are fulfilled, the limit of global warming by "well below 2 °C" will be exceeded. In this context, climate projections for the Amazon suggest, amongst other results, an increase in the range of 1.3°C (lower limit under SSP1-2.6) to 6.5°C (upper limit under SSP5-8.5). Unlike temperature, positive and negative anomalies are expected for precipitation depending on location. Despite the uncertainty regarding the projections, possible changes such as forest diebacks and savannization may take place, namely in southeastern Amazon, by the end of the century. Overall, this study highlights the importance of carefully considering the combination of different factors, such as deforestation, to guarantee rainforest resilience under climate-driven changes.

Keywords: Amazon rainforest; Short-term policy scenarios; National Determined Contributions (NDCs); Shared Socio-economic Pathways (SSPs); Historical climatic trends; Future climate projections; Normalized Difference Vegetation Index (NDVI).

1 Introduction

The future of the Amazon is a topic of global concern, argued to be one of the essential terrestrial systems for the equilibrium of the global climate system (IPCC, 2013a). It is one of the largest ecosystem carbon pools on Earth (Barlow et al., 2018), storing around 150–200PgC in living biomass and soils (Brienen et al., 2015; Feldpausch et al., 2012). The Amazon accounts for approximately one-tenth of the terrestrial ecosystem carbon stocks as well as one-tenth of global net primary productivity (Melillo et al., 1993), which are vulnerable to climatic change (Boisier et al., 2015; IPCC, 2013a; Malhi et al., 2009). Indeed, global increases in mean temperature have a broad range of consequences, which have been widely documented (IPCC, 2014a); for instance, extreme weather events and related impacts, such as droughts and wildfires, reveal the vulnerability and exposure of the Amazon ecosystem (IPCC, 2013a). In fact, the region has been experiencing these extreme weather-related disasters since the 1980s (Brando et al., 2014; Cook and Vizy, 2008; Cox et al., 2008; Oliveira et al., 2005), in particular multiple severe droughts in the past two decades (Marengo et al., 2008; Zhao et al., 2017; Jimenez et al., 2018), leading to tree mortality and reduced carbon sink (Yang et al., 2018). Additionally, intensification of the hydrological cycle is argued to be driving progressively greater differences in Amazon peak and minimum river flows (Gloor et al., 2013). Wongchuig Correa et al. (2017) refer that an increase in hydrological extreme events has been noted in recent decades, for instance, the floods of 1989, 1999, 2006, and 2009. In the future, it is unclear how the terrestrial carbon sink will evolve and how climatic changes and extreme events will affect the Amazon forest vegetation, as the atmospheric greenhouse gas (GHG) composition changes (Brienen et al., 2015), and climate scenarios accordingly.

Regarding GHG emissions, the Paris Agreement reflects the latest stage of implementing international mitigation efforts and involves 1.5/2°C temperature targets by 2100 (Morseletto et al., 2017; Stocker et al., 2013), based on the latest scientific understanding of systemic global warming risks (Schellnhuber et al., 2016). The concept of stabilizing global temperatures is also strongly linked to the Nationally Determined Contributions (NDCs), prepared for the COP-21 Paris Climate Conference in 2015 (UNFCCC, 2015) and ratified by 168 countries on November 4th, 2017 (UNEP, 2017).

1.1 Amazon tipping point

Assessments of the Amazon future and risks of forest loss have changed over time (IPCC, 2014a). Previously, IPCC assessments (IPCC, 2007) stated that a temperature increase of more than 3°C could lead to forest losses of about 40% in parts of the Amazon, driven by a 60% increase in wildfires.

For its part, Nepstad et al. (2008) pointed out that even without raising issues of fires and global warming, interactions among Amazon land use, forests and climate could lead to the replacement or severe degradation of more than half of the closed-canopy forests by a near-term future. Regarding the long term, however, these authors suggested that worldwide reductions of GHGs could prevent global temperatures from rising more than a degree or two and so avoiding the Amazon forest dieback.

Additionally, Cook and Vizy (2008) projected that the rainforest might be reduced by 70% by the end of the twenty-first century, and a wide expansion of caatinga vegetation (mixed shrubland and grasses) on the east Amazon; these changes are associated to decreases in annual mean rainfall and a modification of the seasonal cycle. Finally, in recent years the stability of the Amazon can be argued to have two "tipping points", namely a 4°C increase in global warming or a deforestation threshold of 40% of the forest area (Nobre et al., 2016).

Plausibly, a 4°C threshold in global climate change may affect the Amazon regional climate irreversibly (IPCC, 2007; Sampaio et al., 2007), creating both short-term (e.g., extreme droughts) and long-term hydrologic changes (e.g., different biome distribution) (Sampaio et al., 2019); it may even cause savannization in most of the central, southern, and eastern Amazon (Lovejoy and Nobre, 2018). In fact, according to these authors, the more severe droughts of 2005, 2010, and 2015-16 may represent the "first drops" of the ecological tipping point in the Amazon. The "good news" suggested by the authors is that it is still possible to "build back a margin of safety" by an active and fast reforestation of 23% of destroyed forest territory, such as abandoned croplands and cattle ranches (Lovejoy and Nobre, 2019).

1.2 Forest conservation

Climate-based risks are intertwined with human-induced forest stress. From a top-down management perspective, protected Amazon areas have been inadequately resourced (de Area Leão Pereira et al., 2020; Watson et al., 2014). This condition stresses the importance of both policies and high capacity in enforcement management (Müller et al., 2013) to avoid deforestation in protected forest areas (Killeen et al., 2007). Other solutions are more based on a bottom-up approach. For instance, in several countries, illegal logging and mining involve a denunciation (Pfaff et al., 2013), such as mining reported by indigenous communities in the Venezuelan Amazon (Survival International, 2015).

Dwelling into the top-down approach, Brazil confirmed emissions reduction targets in 2008, including an 80% reduction in deforestation in the Amazon by 2020 (Carvalho et al., 2017). Accordingly, the decline in its deforested area per year between 2008 and 2019 was 75% (INPE, 2019). Via the Paris Agreement, Brazil additionally committed itself to 12 million hectares of reforestation by 2030 (Lovejoy and Nobre, 2018). Although these commitments might look promising, Viola and Franchini (2018) warn of a negative spiral regarding Amazon climate commitment. They describe three types of behaviour regarding the Amazon that have negatively affected Brazilian climate commitment: Amazon Paranoia, Amazon Impotence, and Amazon Neglect. The first behaviour is based on the notion that the Global North desires the Amazon and its resources. The second reveals the notion that deforestation is unstoppable. The third behaviour is grounded on the notion that, even if stopping deforestation is possible, it is not a policy priority. Although Brazil was able to overcome the first two types of behaviour, Amazon Neglect has been rapidly increasing since 2011. Indeed, recent policies have reduced funds for forest inspection and control, as well as lowered environmental restrictions and facilitated the expansion of livestock farming (de Area Leão Pereira et al., 2020) and biofuel production (Ferrante and Fearnside, 2020).

Regarding the bottom-up conservation approach, this involves community-based conservation (human-dominated), such as community-managed forests (Seymour and Busch, 2016). Other initiatives focus specifically on indigenous peoples as environmental stewards, focusing on mutual relationships with nature (Barlow et al., 2018; Gudynas, 2011) and embracing indigenous knowledge systems as valid knowledge on conservation (Tengö et al., 2014). Certain complexities exist in these people-and-nature approaches because of their multi-layered nature (Barlow et al., 2018; Mace, 2014; Ostrom et al., 2009), but in terms of avoiding deforestation, they appear efficient; when we compare various types of protected areas, the areas managed by indigenous peoples are historically less deforested than areas managed by regional and state government authorities (INPE, 2019).

A third approach to conservation is based on the idea that people need to perceive the benefits of nature to justify conservation (Barlow et al., 2018). Such strategies seek to pursue conservation objectives in human-dominated landscapes. They involve private sector actors and are exemplified by the growth in market-based conservation payment mechanisms, such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation), included in international conventions (UNEP-WCMC/IUCN 2020) and the NDCs (Hein et al., 2018; Moutinho et al., 2011). However, the REDD+ activities are reported to have a low track record (Hein et al., 2018), being unable to address the root causes of deforestation (Bastos Lima et al., 2017; Pfaff et al., 2013). Moreover, these activities may create both risks and opportunities for indigenous people (Duchelle et al., 2014; Gebara et al., 2014); NGOs argue that it implies injustice towards indigenous rights (Rainforest Action Network, 2017; REDD-Monitor, 2010).

On the rocky road to forest conservation, one has to bear in mind that both economic and policy changes have caused decreasing deforestation rates in Brazil. According to INPE, (2019), Brazilian deforestation rates peaked in 2004, and from 2004 to 2012, deforestation rates declined (-20%), although they increased again between 2012 and 2019 (11%). These economic and policy changes implied two policy turning points in 2004 and 2008, as well as falling international agricultural prices (Assunção et al., 2015), which caused changes in relative profits from agriculture compared to earnings from forest or conservation (Pfaff et al., 2013). An important point to stress here is that deforestation is not only a responsibility of the Amazon countries. Global demand for agricultural products has become a key driver of cropland extension in low-income regions (Gibbs et al., 2010). International demand and consumption of soya beans, particularly for fuel and animal feed, are one of the critical causes of deforestation. Meat production in European countries accounts for 75% of soy production in South America (Arima et al., 2011; Gasparri and de Waroux, 2015), and thus EU consumption is an indirect cause of deforestation in the Amazon (Bosse, 2018). As such, international regulations and policies in consumer countries can enforce local laws regarding illegal soya productions, which lead to deforestation that also increases the risks of forest fires (Nepstad et al., 2008; Nobre et al., 2016). In terms of competing land-uses, the potential of protected areas is higher than the actual performance. Thus, it is recommended to increase recognition, funding, planning, and enforcement (Watson et al., 2014), and acting on output prices (e.g., by instating import tariffs upon competing products) and input prices (e.g., subsidizing fertilizer costs), as well as taxes, land exploration requirements, and targeting the lack of alternative employment (Houghton et al., 2012; Pfaff et al., 2013).

Last but not least, it is relevant to retain that, in general, historic forests are more energy-efficient than human-managed forests (Norris et al., 2011), which additionally indicate higher resilience in ancient forests and thus a potentially lower risk of wildfires. Undisturbed rainforest roots can extend as far as 20 meters into the ground - where wet-season rain is stored (Lindsey and Simmon, 2006; Saleska et al., 2007). Nevertheless, forest regrowth is an essential element of the vegetation re-emergence potential (INPE, 2017, 2009; Walker et al., 2009), and the best option after deforestation (Nobre et al., 2016). In 2009, around 20% of the deforested area was regrowth forest (Chazdon et al., 2016; INPE, 2009), equalling 3% of the pre-1970 Brazilian Amazon. However, the conversion of ancient forests to plantations appears ecologically, economically, and socially non-sustainable.

1.3 Integration of science and policy

When vegetation is removed or managed by humans, changes in thermal regime (Norris et al., 2011; USEPA, 2019) and human activity increase the risk of wildfires (Patton et al., 2019). Integration of science and policy fields (Barlow et al., 2018), involving national and local governments, conservation actors such as indigenous groups, and technologies such as remote sensing, supports ecosystem and conservation monitoring (Rose et al., 2015).

Regarding applied science, technological opportunities for data collection have been revolutionized by developments in remote sensing and drones (Barlow et al., 2018). They are used to monitor the effects of climate on ecosystems, ecosystem response, and resilience to multiple stressors, informing on the configuration of protected areas, and helping in evaluating the effectiveness of conservation efforts. Such developments may save governmental costs, increase sensitivity awareness (Rose et al., 2015), and thus the effectiveness of anticipating actions in time. In this sense, the Brazilian system of socio-economic planning (ZEE) and the Bolivian Función Económica Social (FES) represent national systems of local strategies (Müller et al., 2013; Oliveira et al., 2010). Such systems represent frameworks of dynamic processes with sole authority, which could strengthen local conservation management (Müller et al., 2013). Notwithstanding, one should also bear in mind that local socio-economic plans can be expected to change, considering the combined effects of temperature increases, precipitation patterns, vegetation removal, and forest fires. Thus, precautionary principles would support ongoing science and policy integration to guarantee sustainable economic, social, and environmental developments. Although traditional policy thinking comprised a perception of a trade-off between forest protection and local economic growth (Carvalho et al., 2017) that may not exist (Kauano et al., 2020). In fact, a lack of forest protection may end up being more socially and economically costly (Abessa et al., 2019; Barlow et al., 2018).

In this paper, we aim to provide an accurate as possible contemporary assessment of how the Amazon climate and its vegetation have been evolving in the recent past, as well as how it may change throughout this century.

The paper proceeds as follows. Section 2 presents the study area, as well as the datasets and methodology used in our analysis. Section 3 comprises: the analysis of precipitation and temperature spatiotemporal historical trends (section 3.1); assessment of mean annual NDVI sum and its spatiotemporal historical trends (section 3.2); and an analysis of climate projections for precipitation and temperature (section 3.3). Finally, section 4 provides an overview of our findings.

2 Material and methods

2.1 Study area

The study area is defined by the Amazon biogeographic limit (RAISG, 2020). The Amazon rainforest comprises different climate zones. According to Köppen-Geiger's classification, the northwest is characterized by a tropical rainforest climate (Af) and monsoon climate (Am). At the same time, the southeast is tropical but with dry winters (Aw), as illustrated in Fig. 1 (left). For projected future conditions, Beck et al. (2018) produced a map from an ensemble of 32 climate models (from CMIP5) under the Representative Concentration Pathway 8.5 (RCP8.5); see Fig. 1 (right). It shows that by 2100 the most critical projected changes are identified in the Southern Brazilian Amazon, where "Tropical savanna climate" (Aw) seems to be expanded, whereas the wetter *Af* and *Am* are becoming more circumscribed. The analysis of climate projections for precipitation and temperature will be further explored in section 3.3.

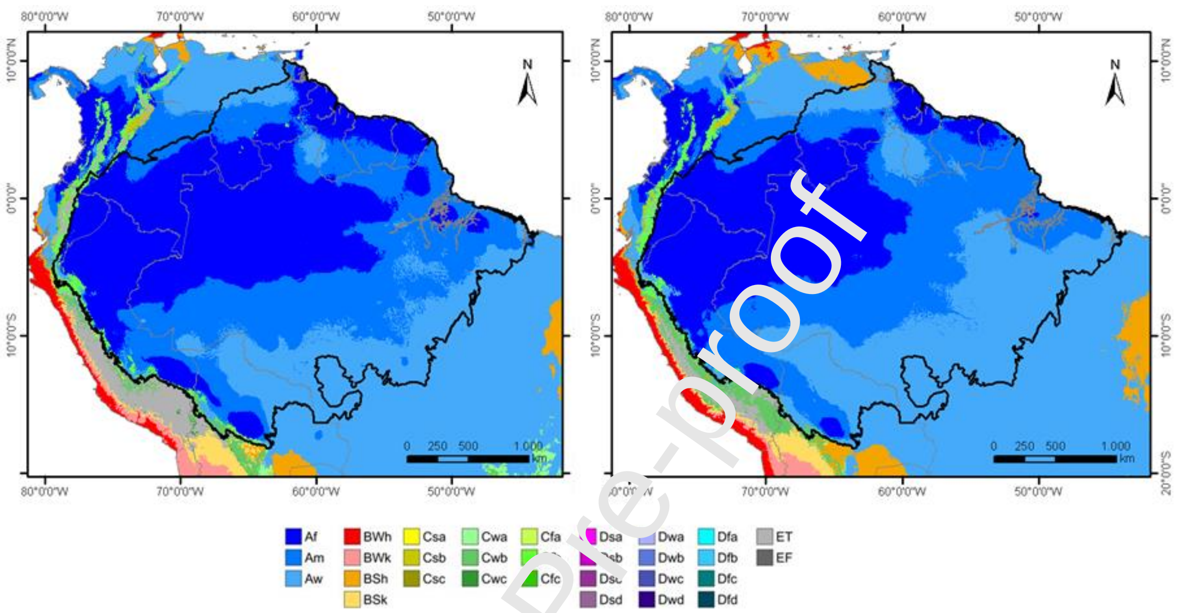

Fig. 1. Characterization of the climate of the Amazon rainforest according to the Köppen-Geiger's classification: left (a) observed climate (1980-2016); right (b) projections for the end of the century (2071-2100) under RCP8.5 (Source: adapted from Beck et al. (2018)). The black line represents the biogeographic limit by RAISG - Red Amazónica de Información Socioambiental Georreferenciada (Source: RAISG, 2020).

2.2 Data and methods

This section describes a four-stage methodology: historical temperature and precipitation trends (2.2.1); historical trends in vegetation (2.2.2); climate and socio-economic scenarios (2.2.3); and climate projections of temperature and precipitation (2.2.4).

2.2.1 Historical temperature and precipitation trends

In the first stage, we analyzed climate trends from 1982 to 2015 (34-year period). For this purpose, surface temperatures (2 m) and precipitation amounts from the ERA5 (ECMWF, 2019) reanalysis were used. ERA5 is the most recent climate reanalysis released by the European Centre for Medium-Range Weather Forecasts (ECMWF), replacing the

ERA-Interim reanalysis. According to Hersbach et al. (2020), ERA5 benefits from a decade of developments in model physics, core dynamics, and data assimilation. A major advantage of ERA5 is also its high horizontal resolution of 0.25° × 0.25° (~31 km at the equator), which ensures the spatial representativeness of climate data, to make it closer as possible to the spatial resolution of vegetation datasets (explained in the next section).

Annual trends were analyzed based on non-parametric Mann-Kendall and Sen's methods (Gilbert, 1987). These methods are widely used to explore trends in climatological time series (Gocic and Trajkovic, 2013; Atta-ur-Rahman and Dawood, 2017). Sen's method is used for assessing the slope of a linear trend, while the Mann-Kendall test is useful for estimating the significance of the trend. Trends were considered as statistically significant when *p-value* ≤ 0.05.

2.2.2 Historical trends in vegetation

In the second stage, vegetation dynamics were explored. The Normalized Difference Vegetation Index (NDVI) is the most widely used vegetation index (Zhao et al., 2017), adequately describing the spatiotemporal distribution of the vegetation structure (Fensholt et al., 2009; Melaas et al., 2013; Soudani et al., 2012). NDVI provides a measure of green vegetation cover per pixel of a satellite image, measuring the relative density and health of vegetation for a particular area. NDVI is defined through the combination of the red and near-infrared bands from the satellite sensor:

$$NDVI = (RNIR - RRED) / (RNIR + RRED)$$

where $RNIR$ is the near-infrared reflectance, and $RRED$ is the red reflectance (Tucker, 1979).

Due to the limitation presented by frequent cloud cover in the Amazon, we opted by using the mean annual NDVI sum, instead of more usual indicators (such as the NDVI maximum). To this purpose, we sum NDVI daily values over each year of our time series and average these yearly sums, to obtain an estimate of annual plant productivity along the study period. The annual NDVI sum reflects vegetation greenness throughout the year and is an adequate indicator for long-term inter-annual trend analysis (Bai et al., 2011; Erasmi et al., 2014; Mirasi et al., 2019) such as the 34-year time series analysed here. This type of NDVI-based indicator can be used as a proxy of large-scale plant productivity for regions where climatic conditions restrict the availability of cloud-free images. By using (cloud-free) data from across the study period, this method is less subject to the effects of stochastic cloud cover, which is likely to underestimate maximum NDVI in some years (Karlsen et al., 2018). Therefore, the probability of distinguishing between forested and deforested areas increases, since more than one single observation in time is being used or, in other words, the probability of remote sensing non-clouded days increases. It is also useful when surveying less accessible areas, another typical limitation of rainforest areas (Karlsen et al., 2018; Mongabay, 2020; Vaglio et al., 2017).

To calculate the mean annual NDVI sum, gridded daily NDVI was obtained from 1982 to 2015, projected on a 0.05-degree global grid derived from the NOAA Climate Data Record (CDR) (NCEI, 2019) of Advanced Very High-Resolution Radiometer (AVHRR) Surface Reflectance, based on data from eight NOAA polar-orbiting satellites (Franch et al., 2017). NDVI datasets were then remapped to the ERA5 0.25-degree resolution grid before calculation of the mean annual NDVI sum, using a first-order conservative remapping operator, to match the spatial resolution of temperature and precipitation datasets. All NDVI processing was done using Climate Data Operators (CDO) tools (Max-Planck-Institut fur Metereologie, 2019). Vegetation dynamics were then explored through maps depicting the spatial distribution patterns of the mean annual NDVI sum, as well as its trends, which were obtained via the same methods described above for temperature and precipitation trends.

To strengthen our analysis of vegetation dynamics, we used 1-km resolution MODIS product MOD13A2 V6. This NDVI data catalogue is provided via Google Earth Engine (Gorelick et al., 2017) from NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC) (NASA, 2001). This is particularly useful to assess changes in vegetation due to land-use changes since the granularity of these regions is inherently higher.

The use of MODIS-based NDVI for remote sensing of the Amazon forest has been extensive, despite its challenges (Maeda et al., 2016). During the multiple wet seasons, cloud contamination of greenness data is widespread. During dry seasons, about 60-66% of greenness data are corrupted because of biomass burning and aerosol contamination (Samanta et al., 2012). In general, research shows considerable variability in spatial and temporal developments of NDVI over the Amazon (e.g., Atkinson et al., 2011; Maeda et al., 2016). To tackle this problem, we followed conclusions from Maeda et al. (2016), which stated that during July, August, and September, the amount of valid data reaches a maximum close to 95%. Therefore, these three months were selected to assess MODIS NDVI with the highest percentage of valid data and produce a seasonal average between 2010 and 2015. This period was chosen since its upper limit is aligned with the previously analysed AVHRR data, but with a much higher spatial resolution. MODIS NDVI calculations were performed in Google Earth Engine.

Finally, since climate change and deforestation are argued to be a critical combination, complementary information on this issue was produced. Therefore, we created a map of accumulated deforestation from 2001 to 2018. Percentual loss of forest area during the same period was also calculated for the whole study area, Brazilian Amazon, and the Amazon forest area excluding Brazil. These calculations were performed using forest cover in 2000 as a baseline and aggregating deforested areas from 2001 to 2018, with data collected from Hansen et al. (2017). Amazon forest cover and deforestation data are currently available from several sources, such as INPE (2019) or RAISG, (2020). We opted for Hansen et al. (2017), given its comprehensive coverage of the Amazon forest area. Otherwise, forest cover and deforestation data for all Amazon countries would have to be collected from different data sources (for instance, INPE deforestation data is limited to the Brazilian Amazon sector), with potentially different data quality levels.

2.2.3 Climate and socio-economic scenarios

Regarding the future, in the third stage, we conducted an evaluation of the short-term scenarios from the parties' current policies and NDCs. Thus, we produced a synthesis of future global climate projections, grounded on ten assessments performed from 2015 to 2019. It is important to compare projections across several assessment teams, as they are based on different methodologies. We focused on four types of short-term scenarios: no-policy (assuming an absence of climate policies post 2005); current-policy (considering the most recent estimates of global emissions and taking into account implemented national policies), unconditional NDC pledges (projecting how global GHG emissions evolve under a successful implementation of the NDCs) and conditional NDCs (assuming financial mitigation support from high-income to low-income countries) (Table 1). Additional details on the four types of short-term scenarios reviewed here can be consulted in UNEP (2019).

Table 1. Projected global greenhouse gas emissions by 2030 and projected increase in global mean temperatures by 2100 above preindustrial levels, according to no-policy, current-policy, unconditional, and conditional NDC pledge scenarios (for each scenario, temperature values are provided for the median emission estimates at the 66% probability level).

Institution	$GtCO_2e$/year by 2030 (median estimate)					Global mean temperature increase by 2100 (ºC)				Data source
	No-policy Baseline	Current policies	Unconditional NDCs	Conditional NDCs	Paris goal (Below 2°C)	No-policy Baseline	Current policies	Unconditional NDCs	Conditional NDCs	
UNEP 2019	**64**	**60**	**56**	**54**	**41**		**3.6**	**3.2**	**3.0**	(UNEP, 2019)
2018	65	59	56	53	40			3.2	3.0	(UNEP, 2018)
2017	64.7	58.9	55.2	52.8	41.8			3.2	3.0	(UNEP, 2017)

2016	64.7	59.4	55.5	53.4	41.8		3.6	3.2	3.0	(UNEP, 2016)
2015	65	60	56	54	42		4	<3.5	<3.0	(UNEP, 2015)
CAT 2019	**60-82**	**55-58**	**55**	**52**		**4.1-4.8**	**3.0**	**2.8**	**2.5**	(CAT, 2019)
2018	60-82	57-60	57	54		4.1-4.8	3.3	3.0	2.7	(CAT, 2018)
2017		56-59	58	54		4.1-4.8	3.4	3.2	2.8	(CAT, 2017)
2016		58-61	56	53		4.1-4.8	3.6	2.8	2.8	(CAT, 2016)
2015			55.1	52.3		4.1-4.8	3.6		2.7	(CAT, 2015)

The evaluation of NDCs based on the two most recent policy assessment studies implies greenhouse gas (GHG) emissions in the range of 52-56 $GtCO_2e/yr$, which in turn leads to projected global mean temperature increases of 2.5-3.2ºC by 2100. The fulfilment of these NDCs implies lower GHGs when compared to current policy assessments. Conversely, the range of projected temperature increase including current policies and NDC signals a global mean warming of 2.5–3.6ºC by 2100 (CAT, 2019; UNEP, 2019; Rogelj et al., 2016).

Regarding their corresponding emissions, the current policies, unconditional, and conditional NDCs altogether, result in global Kyoto-GHG emissions in the order of 52-60 $GtCO_2e/yr$ in 2030, respectively. This results in an emission gap between 11 and 19 $GtCO_2e/yr$, which points towards temperatures higher than 2.0°C, when comparing with the goal of the Paris Agreement by 2030 (UNEP, 2019). Even so, current policies and NDC pledges are remarkably lower than the presented no-policy scenarios (above 60 $GtCO_2e/yr$, considering the entire range).

The NDC assessments considered here convey the notion that NDC pledges are not on track to meet the targets of the Paris Agreement. A shift to a 1.5 or 2°C pathway still requires immediate, substantial, and sustained global mitigation efforts (IPCC, 2018; Raftery et al., 2017). Depending on the level of ambition in national climate policies, the world is on track for global temperature increases between 2.5 and 3.6°C by 2100, according to the most recent estimates (Table 1). Indeed, several authors estimated this level of warming, with very different results, but concluded that current pledges are ineffective to reach a warming below 2°C, let alone 1.5°C (Gütschow et al., 2018; Rogelj et al., 2016).

Recently, within the preparation of the sixth assessment report (AR6) by IPCC, the scientific community has developed a new set of emission scenarios driven by different socio-economic assumptions, called "Shared Socioeconomic Pathways" (SSPs) (O'Neill et al., 2016). Some of these scenarios have been selected to drive climate models for the Coupled Model Intercomparison Project Phase 6 (CMIP6). Concerning the full range of CMIP6 temperature projections, SSP scenarios comprise temperature increases from 1.4°C in SSP1-1.9 and 1.7°C in SSP1-2.6, to above 4°C for SSP3-7.0 and 4.9°C in SSP5-8.5 by 2100, relative to pre-industrial levels (Gidden et al., 2019; Meinshausen et al., 2019). Thus, it is relevant to bear in mind that SSP1-1.9 and SSP1-2.6 were designed considering the warming limit targets of 1.5°C and 2°C established in the Paris Agreement (Chen et al., 2020).

Tribett et al. (2017) compared global emission from INDCs to the previous generation of climate scenarios, based in Representative Concentration Pathways (RCPs), claiming that RCP4.5 is particularly important, signalling a reasonably good probability (~75 %) that the Paris target will be achieved, and an excellent probability (>95 %) that the upper limit for global warming will be attained, if the future atmospheric abundance of GHGs follows this scenario. Later on, (Gidden et al., 2019) compared the trajectories of SSPs with RCPs in terms of radiative forcing levels until 2100, evidencing a strong agreement between the trajectories of SSP2-4.5 and RCP4.5. Therefore, SSP2-4.5 may represent a contemporary "best-guess" projection of how global developments will affect the future Amazon climate, but this may change according to future policy and societal developments. Thus, we decided on using a wider range of scenarios which will be explored in the next section, including both climate goals (SSP1-2.6), medium (SSP2-4.5), medium-high (SSP3-7.0), and high (SSP5-8.5) cumulative emission trajectories, collectively labelled "Tier-1" (Gidden et al., 2019).

2.2.4 Climate projections of temperature and precipitation

In the fourth stage, considering the climate scenarios explored along the above section, projected changes in annual temperatures and precipitation were analysed for the end of the century.

A very limited number of high-resolution simulations are currently available from CMIP6. In this study, we used CMIP6 downscaled future climate projections with a spatial resolution of 10 arc-minutes (~18.5 km at the equator). Downscaling and bias correction were carried out with *WorldClim v2.1* as baseline climate (Fick and Hijmans, 2017). The database is available for download at http://worldclim.org/.

The simulated evolution of future climate is subject to uncertainties, so it is advisable to use the largest possible model ensemble, in order to achieve robust results. Thus, an ensemble was obtained from eight available CMIP6 models: BCC-CSM2-MR; CNRM-CM6-1; CNRM-ESM2-1; CanESM5; IPSL-CM6A-LR; MIROC-ES2L; MIROC6; and MRI-ESM2-0. In order to cover a broad bandwidth of future climate evolutions, all four available scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) were considered. Finally, projected anomalies were calculated for the long-term (2081-2100), concerning the reference period from 1970 to 2000.

3 Results and discussion

3.1 Historical temperature and precipitation trends

Regarding the current climate, results show that annual mean temperatures over the Amazon are around 25°C (Fig. 2, left), ranging between 8ºC and 28ºC. However, these extremes occur only in a few areas. Temperatures below 20ºC occur mainly in the Andes, following the western geographical limit from Bolivia in the south to Colombia in the north. In the Peruvian Amazon, annual mean temperatures differ from about 15ºC in the Andes to almost 26ºC in the rainforest area (Lavado Casimiro et al., 2012). Additionally, temperatures above 26ºC are shown in the east Amazon in the Brazilian state of Pará, spreading to areas in the central Amazon following the Amazon River.

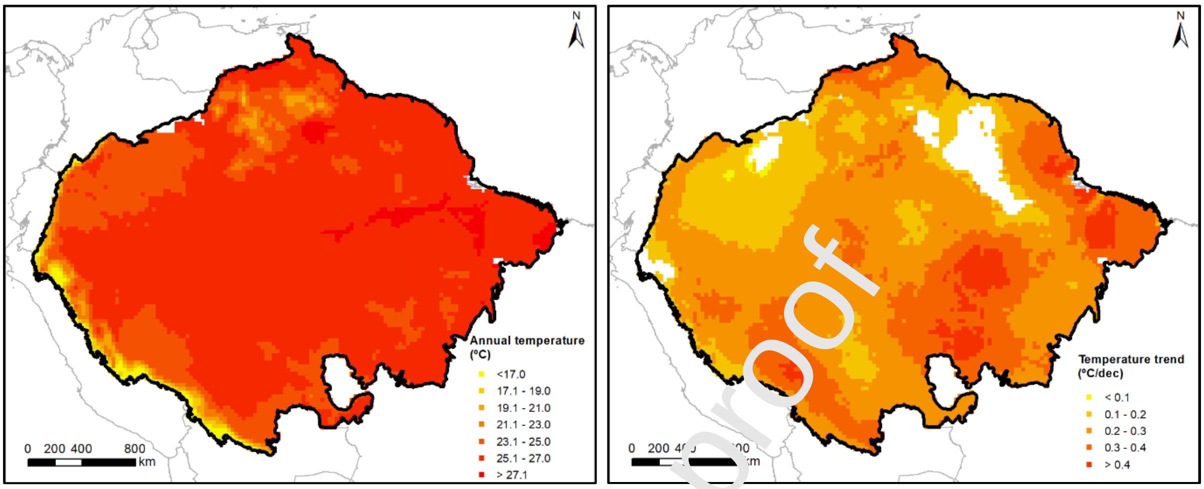

Fig. 2. Annual mean temperature (left) and trends of annual mean temperature (right) over the Amazon for the historical period (1982-2015); trends are not statistically significant in colourless areas (right), according to the Mann-Kendall test.

Over the last decades (1982-2015), our analysis of annual trends suggests an increase of temperature around 0.2-0.3ºC/decade (middle class), which is statistically significant and generally spread all over the Amazon, see Fig. 2 (right). This figure shows that regions with higher increases are mostly found in the southeast Amazon area. Towards the north, a large area stands out where trends are not statistically significant and were therefore not represented.

Evidence of increasing annual temperature has been reported in several studies. For example, Almeida et al. (2017) stated an increase of 0.4°C/decade for a 41-year period (1973-2013) based on 47 stations spread throughout the Brazilian Legal Amazon. Gloor et al. (2015) report a similar spatial distribution of increasing temperature trends. Contrary to the results shown in our paper, these authors presented decreasing temperatures in parts of the west and south Amazon, which in fact, were mainly not statistically significant. Differences in the patterns might be related to the discrepancy between studied periods (1990-2010 in the case of Gloor et al., 2015), and/or the use of different datasets; these authors used the widely known database from the CRU TS 3.21 (Climate Research Unit time-series dataset version 3.21), whereas ERA5 is used here (as mentioned in section 2, ERA5 is the latest climate reanalysis produced by ECMWF). In fact, Gloor et al. (2015), besides the CRU TS 3.21, also showed results based on UDelawarev3.02 (University of Delaware Climate dataset version 3.02), which resulted in a more irregular spatial pattern in temperatures, and emphasised a strong multidecadal-scale variability of the Amazon temperature.

Compared to temperatures measurements over the Amazon, precipitation datasets resulting from instrumental records, gridded datasets derived through interpolation, or remotely sensed outputs, show more complex spatiotemporal variations. One of the issues for Amazon is the sparse and highly uneven distribution of meteorological stations across its complex geography. In an effort to overcome some of these difficulties, here we show results from ERA5, which is developed by assimilating information from ground observations, satellite observations, and model simulations.

Fig. 3 (left) shows annual mean precipitation over the Amazon for the 1982 to 2015 period. The northwestern Amazon is one of the rainiest regions with around 3000 mm/year, whereas the northeast may reach half of that amount. Trend analysis of annual precipitation for the same period (Fig. 3, right) identified only some areas within the Amazon where trends are statistically significant (represented by black crosses over the map). These regions showed both increasing and decreasing trends. Whereas significant decreasing trends in precipitation occur mainly in the western Amazon (comprising small parts of Ecuador, Northern Peru, Andes, and Colombia) and some circumscribed areas in the east and southeast, increasing trends were noticed in the north and northeast Amazon.

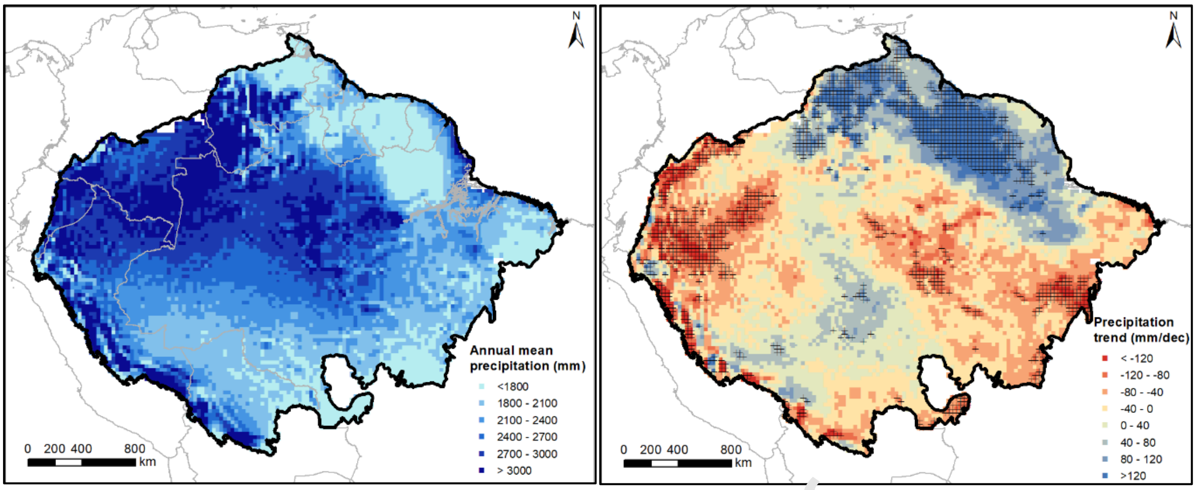

Fig. 3. Annual mean precipitation (left) and trends of annual mean precipitation (right) over the Amazon for the historical period (1982-2015); black crosses represent statistically significant trends (right), according to the Mann-Kendall test.

Gloor et al. (2015) show a similar patchy pattern of precipitation trends distributed over smaller areas of the Amazon. This pattern is recognized by the heterogeneous size of grid zones with positive versus negative trends, depending on used datasets, data selection criteria, and spatial interpolation methodology; these authors showed results based on three different databases (CRU TS 3.21, UDelaware v3.02, and GPCC-Global Precipitation Climatology Center version 6). A recent study by Haghtalab et al. (2020) used the same trend analysis method applied to a similar historical period (1982 to 2018), and based on data from CHIRPS (Climate Hazards Group InfraRed Precipitation with Stations), which incorporates satellite imagery to represent sparsely gauged locations; their findings also identified high variability in rainfall patterns over time and space for the Amazon, and a similar increasing tendency was depicted for the northeast. Still, these authors reported that while the western regions displayed a wetter trend, a dryer trend was noticed in the eastern and southern regions.

According to IPCC assessments, a simple wet-get-wetter and dry-get-drier assumption is not valid for the Amazon (IPCC, 2013a), suggesting that no linear trends can be expected.

3.2 Historical trends in vegetation

Considering the 1982-2015 period, the highest values of mean annual plant productivity (mean annual NDVI sums) over the Amazon occur in the upper north and some southern areas, notably in the southeast corner (Fig. 4, left). As vegetation is associated with precipitation, temperature, land use, the interpretation of their relationship to uncover patterns is a challenge. For instance, concerning precipitation and temperature, strong positive and significant correlations between vegetation communities of grassland and forest and these two climatic factors were reported for the upper Yellow River catchment area, China (Hao et al., 2012). These associations can have a different magnitude and signal, according to plant species (Chuai et al., 2013) and vegetation decay. Adepoju, Adelabu, and Fashae (2019) reported negative correlations with temperature for savanna, settlements, and degraded forest, confirming ongoing land degradation.

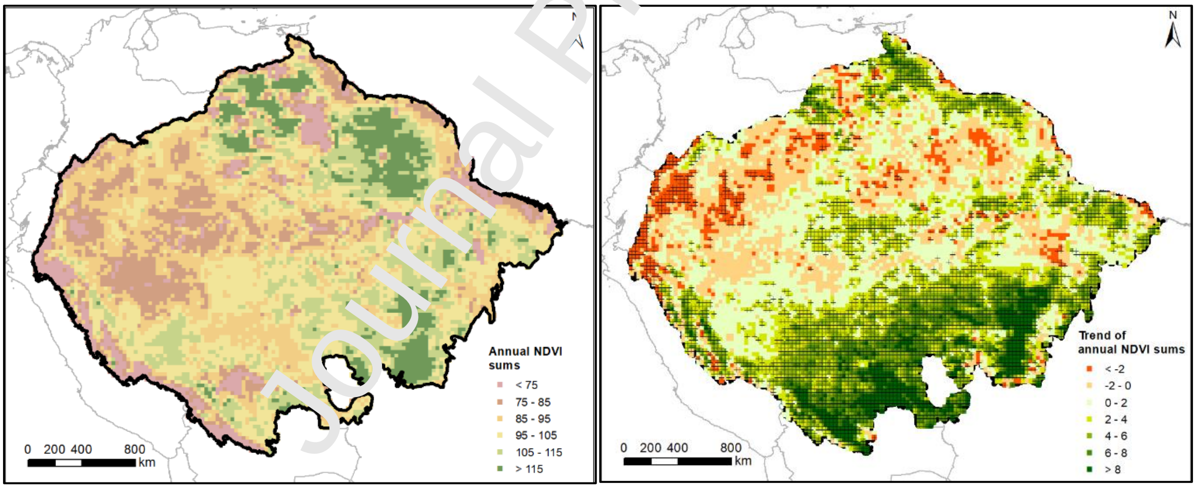

Fig. 4. Mean annual NDVI sums (left) and trends (right) over the Amazon for the historical period (1982-2015); black crosses represent the statistically significant trends, according to the Mann-Kendall test.

Figure 4 (right) shows that significant increases in plant productivity have been prevailing over decreasing trends. Indeed, significant negative trends occur mainly in northwest Amazon. Conversely, greening trends occur mostly in the southern area and, to a lesser extent, in the upper north, along the course of the Amazon river, and across the southwest border (in the Andes). The greening (browning) trends observed in the northeast (northwest) can be related to the increasing (decreasing) precipitation trends previously observed in Fig. 3 (right). Nevertheless, this exploratory analysis also reflects the importance of considering changes in land use. Indeed, the effect of croplands can contribute to a very high NDVI signal in a specific period of the year. Therefore, a possible explanation for the historical greening trend detected in the southeast area (Fig. 4, right) may be the impact of deforestation and subsequent replacement of rainforest with agriculture, which can also depict high values of mean annual plant productivity. For instance, NDVI values for healthy soy plants can reach up to 0.9 (Berger et al., 2019), which is especially relevant, considering soy production is a major driver of deforestation in the Amazon basin (Fearnside, 2001; Nepstad et al., 2014). This is also supported by our trend analysis and recent land cover information (MapBiomas, 2017).

Complementary mean NDVI analysis results, based on higher resolution MODIS imagery for the 2010-2015 period (Fig. 5, left), display lower values for areas also noticed for their lower mean annual NDVI sums in the previous AVHRR-based analysis results (Fig. 4, left). Examples include two mountainous areas (red arrows in Fig. 5, left) and the Amazon river course (a west-east stripe crossing the basin). Additionally, some areas displaying low mean NDVI values (Fig. 5, left) seem to coincide with croplands and new logging areas defined by deforestation, particularly along the southeast border (Fig. 5, right).

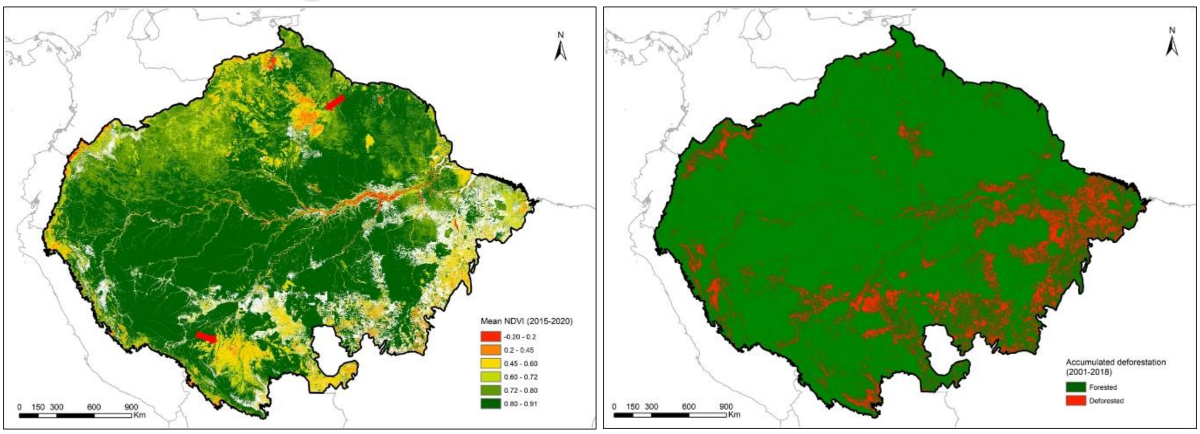

Fig. 5. MODIS NDVI seasonal average between 2010-2015, considering July, August, and September data; two areas with low vegetation (red arrows) (left). Accumulated deforestation (red), forest cover (green), from 2001 to 2018 (right).

To provide a notion of the relative importance of deforestation patterns in Fig. 5 (right) for the whole Amazon area, we calculated that 7% of the Amazon forest cover present within the biogeographical limit has been deforested since 2000. The largest deforested area within this period belonged to the Brazilian Amazon (9%), while deforestation of the Amazon forest in countries excluding Brazil amounted to 3%.

Other authors have already reported the rhythm of deforestation, and although their analyses pertain to different periods, their results illustrate similar trends. For instance, prior to our research, the most recent estimate of total accumulated deforestation between pre-1970 and 2018 in the Brazilian Amazon (which accounts for sixty percent of the Amazon basin) is 17% (Coca-castro et al., 2013; INPE, 2019). Regarding the remaining Amazon countries, it is difficult to establish a trend, but since 2012 overall rates declined in Peru and Bolivia, stabilized in Ecuador, and increased in Colombia (Finer and Mamani, 2020; Hansen et al., 2013). If deforestation ceases and Brazil fulfills its 2030-deforestation commitments, the entire deforested area may reach around 16-17% (Azevedo-Santos et al., 2017; Lovejoy and Nobre, 2018; Marengo and Souza Jr., 2018).

3.3 Climate projections of temperature and precipitation

To better understand possible future changes in the Amazon climate, temperature and precipitation projections were analyzed. For a long-term future (2081-2100), an increase from 1.3 to 6.5°C relative to 1970-2000 is expected, considering the whole range of SSPs (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios) (Fig. 7, left), i.e., assuming the continuation of global emission trends, as well as emission reductions defined by current policies, and those stated in the Paris Agreement. In particular, projections for temperature rise under SSP1-2.6 (the scenario that is consistent with the Paris Agreement goal) and SSP2-

4.5 (the scenario mentioned in section 2.2.3 as a contemporary "best-guess" projection) are remarkably lower (around 1.8 and 3.1°C, respectively) when compared to the highest emission scenario, SSP5-8.5 (around 6°C). Moreover, temperature changes are not equally distributed across the Amazon; an increasing trend is observed in the north-south direction. A drier climate is already present in areas such as southeastern Amazon (Aw, see Fig. 1 left), where the highest temperature increases are expected, which means the risk of droughts can be magnified.

When comparing these results with projections from RCP scenarios, an apparent higher increase of temperature is expected under SSPs, regarding simulations from CMIP5 for similar forcing scenarios. According to Collins et al. (2013), temperature projections by 2100 in the Amazon are expected to rise around 6°C under RCP8.5, up to 3°C under RCP4.5 and up to 1.5°C under RCP2.6, relative to 1986-2005. Regarding SSPs, as illustrated in Fig. 7, temperatures may rise around 6°C under SSP5-8.5, up to 3.5°C under SSP2-4.5, and up to 2.2°C under SSP1-2.6. As these findings derive from relatively few models (eight), they should be treated with caution until more models are available.

Fig. 7 (right) portrays projections of precipitation anomalies. An increase is only expected for precipitation in the west outer limits, whereas a decrease is projected all over the rest of the Amazon, especially in the top north between Venezuela and Guyana boundaries. Precipitation anomalies are projected to range between -30 to +30%; particularly, in the transition between decreasing and increasing trends, anomalies are close to zero. The spatial distribution of anomalies bears a similar pattern across all four scenarios, which intensifies from SSP1-2.6 (mean of -1%) to SSP5-8.5 (mean of -9%).

Throughout the assessment of past climate trends (section 3.1), annual mean precipitation trends were mostly not statistically significant. Nevertheless, an increase was observed in the northern and north-eastern Amazon, comprising parts of Venezuela, Guyana, Suriname, and the Brazilian State of Pará. This apparent increase should not be taken as guaranteed since, according to long-term projections, this area is expected to get drier by the end of this century.

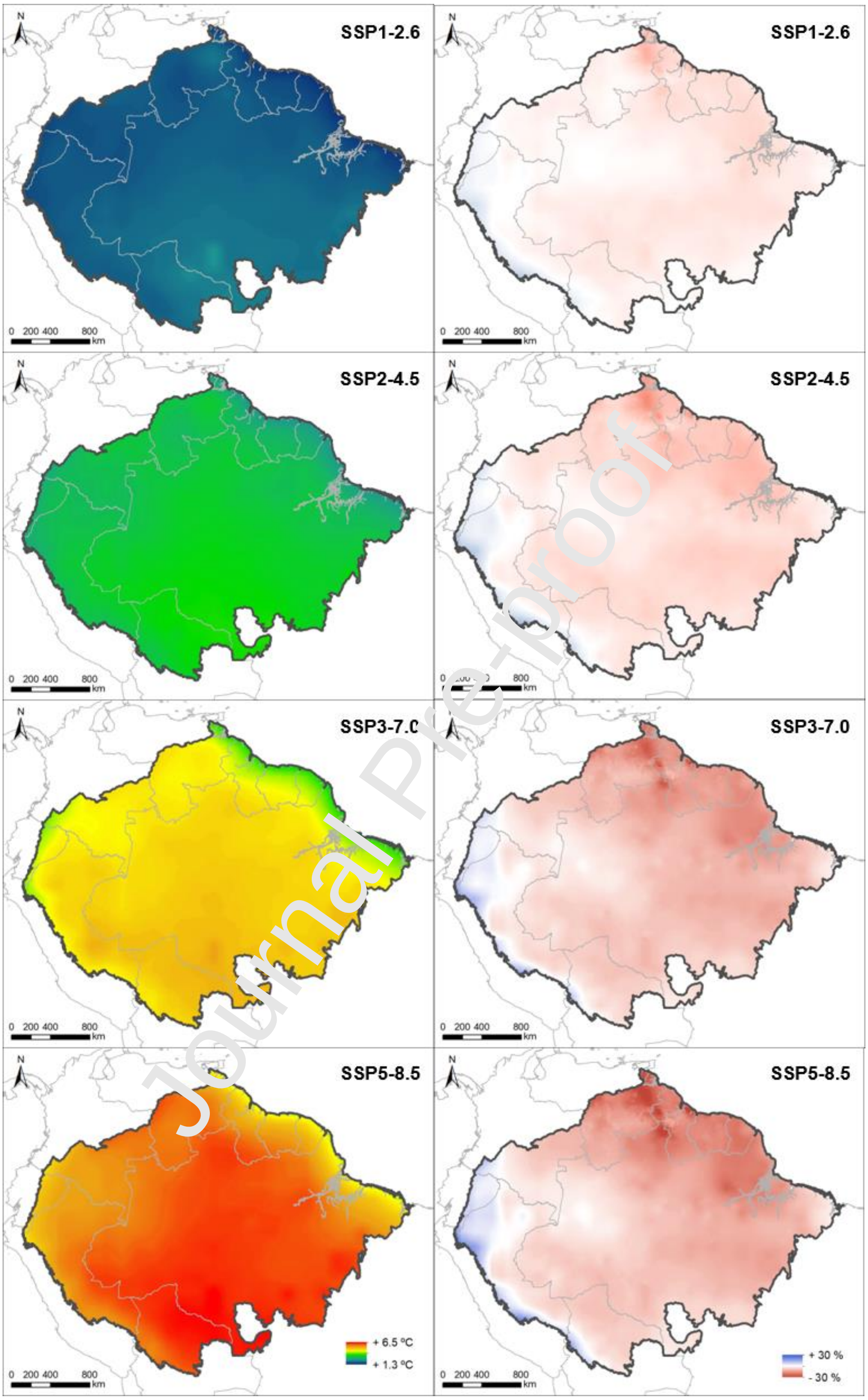

Fig. 7. Anomalies of annual mean temperatures for the Amazon basin for the period 2081-2100, under the scenarios: SSP1-2.6 (first row left); SSP2-4.5 (second row left); SSP3-7.0 (third row left); SSP5-8.5 (last row left**).** Anomalies of annual mean precipitation for the Amazon basin for the period 2081-2100, under the scenarios SSP1-2.6 (first row right); SSP2-4.5 (second row right); SSP3-7.0 (third row right); SSP5-8.5 (last row right).

The projections shown in this study are in alignment with the IPCC results for similar forcing scenarios for the end of the century (2081-2100 in relation to 1986-2005) (IPCC, 2013b). Nevertheless, as mentioned for temperatures, projections from CMIP6 suggest wider trends than those from CMIP5. Regarding RCP2.6, decreasing precipitation up to 10% is projected from the north-northeast to south and center of Amazon, whereas an increasing trend up to 10% will be mainly expected towards the western Amazon comprising Colombia and Peru. Under RCP8.5, a strip with a higher decreasing magnitude (up to 20%) will be extended from the north-northeast to the southeast.

The complexity of the Amazon climate prevents us from signalling linear trends. Nevertheless, general patterns were identified for specific areas; a trend of dry-gets-drier for the southeastern Amazon and wet-gets-wetter for the southwestern border (the Andes) is possible in all four SSP CMIP6 scenarios. These changes can be particularly critical if we have in mind that, according to IPCC assessments, extreme precipitation events over most of the mid-latitude land masses and wet tropical regions will very likely become more intense and more frequent (IPCC, 2014b).

4 Final remarks

Based on an interdisciplinary approach, we have assessed the past and future of the Amazon rainforest, considering plausible middle to long-term emission pathways and political strategies.

In general, a significant temperature increase of about 0.2-0.3ºC per decade was found between 1982-2015 all over the studied area. Unlike temperature, trends in precipitation were only significant for limited regions; in particular, decreasing trends were detected mainly in the western Amazon, and some circumscribed areas spread in the East-southeast part, while significant increasing trends were detected in the north-northeast Amazon.

As expected, climate projections show less spatial variation than the results of historical trend analysis, which emphasizes some limitations of used climate models. Despite its uncertainty, the highest projected temperature increases are expected in southeastern Amazon, a result that is relatively consistent with the historical trend. A temperature increase between 4°C to 6.5°C is to be expected, under the SSP5-8.5 scenario, for the Amazon. However, this is less likely under present policy scenarios assessed in this study. Indeed, full completion of the NDCs may push temperatures down to a range of 2.2°C to 3.5°C, under the SSP2-4.5; and following the ambitious goal of the Paris Agreement, temperatures increase between 1.3 and 2.2°C, under SSP1-2.6.

Regarding precipitation, decreasing trends are projected, ranging from the northernmost tip to southeastern Amazon, as well as higher amounts of precipitation for the outer areas of the southwest (the Andes). It should be noted that further studies making use of Regional Climate Models developed from dynamical downscaling may improve estimations of future climate, as this represents an initial assessment, using a subset of CMIP6 models.

Does this mean that the Amazon rainforest will endure these projected future climatic changes? For the Amazon, a tipping point of 4°C increase in global temperature is generally accepted. Therefore, Amazon endurance may occur under current global mitigation policies, which estimate global temperature increases between 2.5 and 3.2°C. However, our findings suggest that the projected climatic changes may lead to environmental, social, and economic loss, weakening Amazon provinces and states. The most vulnerable areas are the ones that are more exposed to deforestation and land-use change, such as the Brazilian State of Pará (eastern Amazon), where increasing temperatures, along with decreasing precipitation trends and heavy deforestation, have been observed.

The relatively stable character of the ancient Amazon forest, compared to the arguably more vulnerable and less resilient conditions of regrowth forest and human-managed forests, points out an opportunity to periodically review and update local and regional policies. This opportunity (and need) stems from current potential risks presented by socio-economic activities. Trade-offs have been perceived in traditional policymaking between economic interests and conservation practice. A lack of forest protection may end up being more socially and economically costly than those trade-offs. Avoidance to act decisively and now will intensify the risk of reduced forest resilience and unprecedented and irrevocable biodiversity loss, which in turn may lead to social and economic crises. Achieving these changes requires interdisciplinary integration of the natural and social sciences and policy fields, enabling capacity building for conservation and improvement of the knowledge base on the Amazon and its ecosystems. Technological developments in remote sensing may save governmental costs, increase awareness on rainforest sensitivity, and the effectiveness of anticipating actions in time. This implies both national and local governments acting on the Amazon, but also global considerations and policymaking in Europe, North America, and Asia regarding consumption of products that have a negative impact on the Amazon, as well as some potentially overlooked adverse implications of REDD+ initiatives on local communities.

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Highlights

1. Between 1982 and 2015 annual trends suggest significant temperature increases of 0.2-0.3ºC/decade generally spread over the Amazon

1)

2. Strong consensus that if either current policies, unconditional or conditional NDCs are fulfilled, the limit of global warming by "well below 2 °C" will be exceeded

3. Temperature projections for the 2081-2100 period indicate average increases for the Amazon in the range of 4-6.5°C under SSP5-8.5, 2.2-3.5°C under SSP2-4.5, and 1.3-2.2°C under SSP1-2.6

4. Projected temperature increases are unfolding in the north-south direction, projected precipitation decreases are estimated from the northernmost tip of the study area limits to southeastern Amazon, as well as higher amounts of precipitation for the west outer limits (the Andes)

5. The most vulnerable areas are located in the southeastern Amazon with increasing temperatures, decreasing precipitation, and heavy deforestation