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Climatic and ecological future of the Amazon: likelihood and causes of change

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Abstract

Some recent climate modeling results suggested a possible dieback of the Amazon rainforest under future climate change, a prediction that raised considerable interest as well as controversy. To determine the likelihood and causes of such changes, we analyzed the output of 15 models from the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC/AR4) and a dynamic vegetation model VEGAS driven by these climate output. Our results suggest that the core of the Amazon rainforest should remain largely stable as rainfall is projected to increase in nearly all models. However, the periphery, notably the southern edge of the Amazon and further south in central Brazil, are in danger of drying out, driven by two main processes. Firstly, a decline in precipitation of 22% in the southern Amazon's dry season (May-September) reduces soil moisture, despite an increase in precipitation during the wet season, due to nonlinear responses in hydrology and ecosystem dynamics. Two dynamical mechanisms may explain the lower dry season rainfall: (1) a general subtropical drying under global warming when the dry season southern Amazon is under the control of the subtropical high pressure; (2) a stronger north-south tropical Atlantic sea surface temperature gradient, and to lesser degree a warmer eastern equatorial Pacific. Secondly, evaporation demand will increase due to the general warming, further reducing soil moisture. In terms of ecosystem response, higher maintenance cost and reduced productivity under warming may also have additional adverse impact. The drying corresponds to a lengthening of the dry season by 11 days. As a consequence, the median of the models projects a reduction of 20% in vegetation carbon stock in the southern Amazon, central Brazil, and parts of the Andean Mountains. Further, VEGAS predicts enhancement of fire risk by 10–15%. The increase in fire is primarily due to the reduction in soil moisture, and the decrease in dry season rainfall, which is when fire danger reaches its peak. Because the southern Amazon is also under intense human influence as a result of deforestation and land use, added pressure to the region's ecosystems from climate change may subject the region to profound changes in the 21st century.

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1 Introduction

A coupled climate-carbon cycle model study projected a major dieback of the Amazon rainforest towards the end of this century under global warming, with much of the Amazon forest replaced by savanna (Cox et al., 2000, 2004; Betts et al., 2004; Huntingford et al., 2008). That work generated considerable interest as well as controversy. The interest is partly because the Amazon is the largest rainforest in the world, a large carbon reserve, and a region of great biodiversity. The region has also been under the pressure of deforestation which, at current rates, could eliminate 40% of the Amazon forest by 2050 (Soares et al., 2006). A possible susceptibility to human-induced climate change would impose additional danger (Malhi et al., 2008). Due to the potential for large changes in carbon stocks in this region, the Amazon has been listed as a potential tipping element that may lead to a climate change surprise (Lenton et al., 2008).

Controversy surrounding this work comes from several grounds. For instance, some other similar models do not show wide-spread conversion of rainforest to savanna (Cowling and Shin, 2006; Schaphoff et al., 2006). Instrumental and proxy records show that the Amazon rainforest was relatively stable throughout the 20th century, and in the geological past, such as during glacial times and the Holocene warm period (Baker et al., 2004; Malhi and Wright, 2004; Bush and Silman, 2004; Mayle et al., 2004). The controversy is further clouded by the lack of a clear and widely-accepted climate driver and ecosystem response/feedbacks that could lead to such a dieback. At first glance, simple arguments would suggest a wetter Amazonia: It is believed that the Inter-Tropical Convergence Zone (ITCZ), which encompasses the atmospheric convection center over the Amazon, will become stronger in the future due to a more vigorous hydrological cycle driven by global warming (Held and Soden, 2006). Thus, one may expect more rainfall over the Amazon. On the ecosystem side, the large rainfall amount of over 2000 mm y^{-1} in the core of the Amazon Basin supplies abundant water. Due to the frequent rainfall and cloudy sky, it has been suggested that the limiting factor for

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forest growth in the Amazon is sunlight, not water so that even a decrease in precipitation may not necessarily have adverse effect on the ecosystem (Nemani et al., 2003; Huete et al., 2006), although this notion has not been widely accepted either.

Another major factor complicating the issue is that the "Amazon" is not defined in the same way across all studies. and process-level mechanisms suitable for one part of the "Amazon" region are sometimes applied to other parts without sufficient caution. Rainfall in the Amazon and surrounding regions can vary significantly from place to place and over a seasonal cycle (Marengo, 1992; Ronchail et al., 2002; Zeng, 1999). Most notably, precipitation at the core of the rainforest (western Amazon, hereafter WA, broadly represented by a box enclosing 76 W–65 W and 10 S–5 N in Fig. 1;) has double maxima as the sun crosses the equator twice a year. In contrast, the southern Amazon and central Brazil (box in Fig. 1; 65 W–50 W, 20S-5S hereafter SAB) has its rainy season (December–March) in boreal winter with rainfall higher than 6 mm d^{-1}, and a dry season (May–September) with rainfall lower than 1 mm d^{-1}as the ITCZ and associated land convection center move back and forth following solar heating (Fig. 1 and Fig. 13). While the WA also has lower rainfall during May-September, it is still as high as 4 mm d^{-1}. Thus one may reason that water stress may be an important issue affecting rainforest health in the SAB region, but it is not likely to be as critical in western Amazon even during its 'dry' season.

Climate variability such as sea surface temperature (SST) changes in the eastern Pacific Ocean associated with the El Nino-Southern Oscillation (ENSO) is known to have a strong impact on the Amazon, but the center of impact tends to be in the eastern part, or the lower Amazon (thereafter EA) (Ropelewski and Halpert, 1987). Indeed, the Hadley Centre model simulates an initial drying around the lower Amazon, akin to typical El Nino response, consistent with the fact that the Hadley centre model projects a strong perpetual El Nino-like state under global warming (Betts et al., 2004; Cox et al., 2004), and this initial drying progresses further inland as global warming intensifies and land-vegetation feedback reduces water recycling (Betts et al., 2004). In a similar teleconnection, SST patterns in the subtropical Atlantic Ocean tend to affect precipita-

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tion in the southern and southwestern Amazon, as was seen during the 2005 drought (Zeng et al., 2008; Marengo et al., 2008) and over the last three decades (Yoon and Zeng, 2010).

The IPCC AR4 (IPCC, 2007) climate simulations under specified emissions scenarios provide an opportunity to examine the issue of future Amazon change with multiple models. The annually averaged global analysis from the IPCC report does not show rainfall reduction in the Amazon basin (Meehl et al., 2007) (Figs. 2a and 11). Surprisingly, when forced by climate projections from these same IPCC models, vegetation modeling predicts an increase in ecosystem risks such as fire (Scholze et al., 2006) and forest-savannah transition (Salazar et al., 2007) in a large fraction of the Amazon. How is it possible that more precipitation drives higher fire risk and the loss of forest? An immediate possibility is the general warming which could enhance evaporation loss and reduce vegetation growth. In addition, there may be another factor: the interaction between a changing climate and non-linearity in the hydrology and ecosystem dynamics. Specifically, the drying may be seasonally dependent as suggested by recent research (Cook and Vizy, 2008). Ecosystem vulnerability is manifested most strongly during the dry season, as suggested by studies of short-term drought in the Amazon (Zeng et al., 2008; Phillips et al., 2009), so dry-season precipitation may have non-linear impacts on ecosystem health. Such hypotheses largely motivated this study.

Here we analyze 15 IPCC AR4 models for their projected changes in precipitation, temperature, soil moisture, SST, and other relevant climate variables for the Amazon and surrounding regions. We will focus our discussion on the behavior of the median of these models, while showing some individual model results and inter-model ensemble variation. Furthermore, we identify the mechanisms responsible for the simulated changes, thus providing critical information on the likelihood of such changes. We also assess the hydro-ecosystem response to these projected climate changes using a dynamic vegetation and terrestrial carbon cycle model, with particular interest in the nonlinear dynamics and potential feedbacks.

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2 Data and models

The IPCC models used in this study are each multi-model ensembles. Each model is run from 1900–2100. Estimated radiative forcings were used to drive the models for the 20th century. The SRES A1B scenario was used to simulate twenty-first century climate. The A1B emissions scenario was selected as it is a fairly representative average of the different emission scenarios conducted by the IPCC. Scholze et al. (2006) showed that the degree of warming is important to ecosystem response because of the nonlinearity and potential threshold behaviors, but we chose to focus only on one emissions scenario to limit our analysis to a manageable scope with the understanding that more severe or benign responses are possible. The 15 models chosen are among the most widely used by the research community, and are listed in the Appendix. The model output was interpolated onto a common 2.5°×2.5° grid. The change from late 21th century (2070–2099 average) relative to a base period climatology (1961–1990 average) was computed. In this study, we focus on two regions: the core of the Amazon rainforest (western Amazon or WA, 76 W–65 W and 10 S–5 N), and the Southern Amazon and central Brazil (SAB; 65 W–50 W, 20 S–5 S), as shown by boxes in Fig. 1. We also analyzed the eastern Amazon region (EA, 65 W–50 W, 5 S–5 N) and found that the future precipitation change is similar in magnitude to the SAB region but because it is climatologically wetter than the SAB region (similar to WA) the vulnerability to biome change is lower and the results are not discussed in detail here. Box averages for many ecosystem variables in these two regions (SAB and WA) were calculated for both the base climatology period and the future climatology. Then, the median of the aforementioned change and that of the time series were obtained. Percentage change in ecosystem variables relative to the base period climatology was computed for each individual model and the median value across models was obtained in the same manner. The median calculation was always done on the change in a given variable from the 20th to the 21st centuries, not the absolute value.

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One possible drawback to using the median of output from the climate models is that all climate models are given equal weight in the analysis, while not all models do an equally good job in reconstructing the 20th century climatology of Amazonia. In fact, some researchers have attempted to develop metrics which assign different weight to the GCM's based upon their ability to reproduce the climatology of the 20th century (Li et al., 2008). If we were to use this approach, it is likely that our findings that the dry season will see a reduction in precipitation (below) would be even more robust as those models that do a better job in simulating the climatology of the 20th century tend to forecast a reduction in precipitation in the 21th century. However, given that the IPCC's analysis treats all climate models equally, there is no widely accepted criterion to tell 'good' from "bad" models, and the average of climate model output tends to show higher skill than any individual model (Reichler and Kim, 2008), we feel that giving all models equal weighting is the most prudent choice at this stage. Nonetheless, the inter-model variations as well as individual model behaviors will also be presented. We chose to focus on the median of models as opposed to the mean in order to reduce the influence of strong outliers. This process was done for each individual variable, each grid point or each region separately.

The dynamic vegetation and terrestrial carbon cycle model VEGAS (Appendix) was forced individually by the 15 model climates for variables such as precipitation and temperature for 1901–2100, preceded by a spin-up using each climate model's first year output, and then the results were analyzed for their changes so that each model-forced run was treated like an individual model while sharing the same vegetation component.

3 Spatially and seasonally dependent rainfall change

Our results reveal a complex picture in answering the question whether the Amazon will dry out in the future. When comparing the model simulated rainfall in 2070–2099 to that of 1961–1990, median annual rainfall is projected to increase across much of the Amazon basin and South America (Fig. 2a). This change is dominated by in-

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creased rainfall during the SAB's wet season (December–March) (Fig. 2b). However, during the SAB's dry season (May-September), the models show a clear decrease in rainfall in the southern Amazon, extending into central Brazil, northeastern Brazil (Nordeste) and neighboring countries (Fig. 2c). In particular, the GFDL, MIROC, MPI, and UKMO/Hadley Centre models show a greater than 25% decline in precipitation inside the SAB region. Only GISS_ER and IPSL predict an increase in rainfall (Fig. 3). In contrast, the western Amazon tends to have more rainfall for both seasons when the models are averaged, but this is especially true in the SAB's wet season (Fig. 4). We thus focus our analysis on the southern Amazon and central Brazil region which appears to be more of concern in terms of vulnerability.

Temperature in the SAB region is projected to increase by 3–4 °C in the late 21st century, with the largest increase at the end of the dry season (Fig. 5a). For rainfall, the IPCC models suggest that the region will become wetter by more than 0.1 mm d^{-1} on an annual average basis (Figs. 5a and 8a). This is dominated by a wet season increase of over 0.3 mm d^{-1} in the median value (Fig. 5a). However, the increase in precipitation is not spread equally throughout the year. In fact, during the driest time of the year in SAB, precipitation is projected to decrease, but by less than 0.1 mm d^{-1}. Interestingly, the maximum decrease occurs in the transition months of May and October, whereas the driest months of June–August have miniscule reduction because the climatological rainfall is already very low. Indeed, some models have a 20th century climatological dry season that is too dry compared to observations (not shown). As a result, there is a lengthening of the dry season by about 11 days (Fig. 6a). This lengthening of the dry season manifests itself not as an early drying, but mostly as a delayed onset of the wet season, a robust feature in the IPCC models (Biasutti and Sobel, 2009). In contrast, the WA region has slightly more rainfall during the dry season, and interestingly also appears to show delayed onset of the wet season (Fig. 6b).

At first glance, this result would suggest that there is no need to worry about a drying in the Amazon. However, the dry season rainfall reduction becomes prominent when viewed as percentage change. The median change suggests that dry season southern

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Amazon rainfall will decrease by 22% with some areas declining by as much as 40% (Fig. 2c). Out of the 15 models, 11 show significant rainfall reduction in the dry season, two have little change, and two models show moderate increase (Fig. 7a). In contrast, during the wet season the median model predicts an increase in precipitation of 5%, and the individual models are less consistent than during the dry season, nine models become wetter while six become drier (Fig. 7b). Thus the most robust rainfall changes appear to be a "drier dry season" for the SAB region, and a "wetter wet season" for the WA region, as summarized in Table 1. We now analyze how this seasonally dependent change in rainfall interacts with nonlinear dynamics to generate major hydro-ecosystem responses.

4 Hydrological and ecosystem impact

One of the most important linkages between climate and ecosystem health is soil moisture. The predicted change in soil moisture computed from the median of the IPCC models has similar spatial structure to that of the change in dry season precipitation (Fig. 2d). This happens despite the fact that wet season precipitation increases more than dry season precipitation declines. Hence, the change in soil moisture suggests that the amount of precipitation during the dry season is more important to ecosystem health than net rainfall alone. Several nonlinearities in the system may play a role here. Wet season soil moisture is near saturation, so much of the excess rainfall will drain as runoff (Fig. 8h). This is consistent with the observed high Amazon streamflow in late spring shortly after peak rainfall (Zeng, 1999;Zeng et al., 2008). In contrast, a greater fraction of the dry season rainfall is mostly used to recharge the soil water pool, thus it has a disproportionately large impact on soil water storage and ecosystem health.

Another major effect is increased evaporation due to the general warming under climate change. A 3–4 °C warming in the Amazon would significantly increase evaporative demand, regardless of precipitation change. More evaporation by itself tends to reduce soil moisture. The fact that the models project increase in evaporation (Fig. 8c)

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despite the decrease in soil moisture (Fig. 8f), suggests the warming-enhanced evaporative demand is highly effective at depleting soil moisture. Additionally, the higher temperature raises the vegetation maintenance cost, thus further reducing vegetation growth (Zeng and Yoon, 2009).

A drier soil, coupled with a warmer climate, leads to dramatic changes in the ecosystem in the SAB region. By the late 21st century, the VEGAS model, forced by the IPCC climate model projections, shows a decrease in soil moisture by 4%, a decrease of leaf area index (LAI) by about 1.0, a 20% change, and an increase in land to atmosphere carbon flux due to fire from 45 to 51 $g\,m^{-2}\,y^{-1}$ (13%) (Fig. 8). Here, another nonlinearity is responsible for the much larger response in vegetation than in soil moisture, the drier dry season puts greater stress on vegetation at the most vulnerable time of the year (Zeng et al., 2008;Phillips et al., 2009). A similar nonlinearity exists with respect to fire risk. Fire is most prevalent in the Southern Amazon near the end of the dry season (Aragao et al., 2008; Cochrane et al., 1999). A relatively small decline in soil moisture at the end of the dry season can increase fire risk dramatically. This occurs despite the fact that net annual precipitation increases, as the increased rainfall occurs during a time of year when little fire occurs anyway.

The spatial distribution (Fig. 9) of the 21st century vegetation related changes shows wide spread loss of vegetation, beyond the area with 'drier dry season', and needless to say, even more so for the area with lower annual mean precipitation (cf. Fig. 2). LAI decreases by over 0.5 in the southern Amazon, and by more than 1.0 in central Brazil. It is somewhat puzzling that much of the WA region also has a slight decrease in LAI, although the soil moisture is actually somewhat higher. Here another mechanism must have played a role, namely, the warming would increase autotrophic respiration and plants' maintenance cost. In addition, photosynthesis itself may decline at higher temperatures. Across much of these regions, there is increased incidence of fire by the end of the 21st century. Alarmingly, increased fire risk occurs high into the Andean Mountains from Bolivia to Peru and Colombia, apparently driven by the lowered soil moisture (Fig. 2d). An increase in LAI is seen in a small area of the Bolivian Altiplano

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(Fig. 9b), probably due to the warmer temperatures, as vegetation growth in cold, high. mountainous regions is often limited by temperature, not rainfall. Interestingly, this added growth provides additional fuel for fire (Fig. 9a), though it is not clear how strong this impact is, and it requires further study.

The broad changes in vegetation are consistent with a global study, which took a similar modeling approach, using a different dynamic vegetation model LPJ (Scholze et al., 2006). Our analysis of the non-linear hydro-ecological response offers an explanation for the major potential changes in the southern Amazon seen in the models, despite an increase in annual precipitation.

5 Dynamical mechanisms due to SST and circulation changes

Our analysis has singled out the importance of dry season precipitation change on the vegetation in the southern Amazon. The question naturally arises as to the robustness and mechanisms of such changes. The fact that rainfall increases during the wet season suggests that complex factors may be at play. We have identified two aspects of potential importance: tropical atmospheric circulation dynamics and SST changes in the tropical Atlantic and Pacific Oceans.

A significant number of IPCC models predict that under global warming, the equatorial Pacific Ocean will be more El Nino like, i.e., the eastern Equatorial Pacific will be permanently warmer relative to western Pacific than it was during the 20st century, corresponding to a weakening of the Walker circulation (Meehl et al., 2005; Vecchi et al., 2006). It has long been known that such warm SST anomalies associated with El Nino suppress rainfall over the Amazon, particularly the lower Amazon (Ropelewski and Halpert, 1987). A similar warm SST anomaly, relative to a background warming, is clearly seen in the median model (Fig. 2d) and could contribute to the reduced rainfall over the Amazon, especially in some models (Cox et al., 2000). However, El Nino-induced rainfall change tends to be concentrated in lower Amazon (Ropelewski and Halpert, 1987; Zeng et al., 2008) and indeed the drying along the northeast coast of

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South America (Fig. 2a) may be in part a result of this, but the main explanation for a drier southern Amazon must lie somewhere else.

The reduced dry season rainfall may be more related to changes in the tropical Atlantic Ocean (Fig. 2d). The change in the Atlantic SST gradient is very robust as all 15 models show a warmer North Atlantic compared to the South Atlantic (Fig. 10) in the future. This change is likely due to tropical atmosphere-land-ocean interaction in response to greenhouse warming although exactly how it arises has not been identified to our knowledge. This Atlantic SST-Amazon rainfall linkage has recently been identified during an unusual drought in 2005 when a warm subtropical North Atlantic suppressed rainfall by moving the ITCZ northward (Zeng et al., 2008; Marengo et al., 2008; Cox et al., 2008). The subsidence generated by this northward-shifted, stronger ITCZ would lead to drying in the southern part of the Amazon.

Another potential explanation for the decline in dry-season precipitation involves a tropical-wide mechanism. Under climate change, the ITCZ is expected to become stronger and narrower due to warming-enhanced vigorous convection. Correspondingly, the subtropical dry zones will become drier and broader. This tendency for subtropical drying is one of the most robust precipitation signals in the IPCC/AR4 climate projections, sometimes referred to as the expansion of the Hadley Cell (IPCC, 2007; Held and Soden, 2006) (Fig. 11). There may be many factors that contribute to this change, but it is mostly a consequence of atmospheric humidity increase under warming following the simple Clausius-Clapeyron relation: an increase in humidity leads to more moisture convergence, thus more rainfall in the convergence zone; and conversely, more moisture divergence ($\nabla \cdot (qv)$, which increases as humidity q increases exponentially with temperature), thus less rainfall in the divergence/subsidence region (Neelin et al., 2006; Held and Soden, 2006; Seager et al., 2007). This is a change in which “the rich gets richer and the poor gets poorer”.

The question then becomes whether the region in question is part of the ITCZ convection band with upward motion that generates rainfall, or a part of the subtropical atmospheric subsidence zone, where rainfall is suppressed. Climatologically, during

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the dry-season, the southern Amazon and central Brazil lie at the western edge of a subtropical high pressure zone between the Equatorial Amazon convection center and the South Atlantic Convergence Zone (SACZ) (Figs. 12 and 13). As a result, dry season rainfall in this region is as low as 1 mm day^{-1} compared to wet season rainfall of 7 mm day^{-1} (Fig. 1).

Thus, during the dry season, the SAB is essentially part of the subtropical dry zone, and the subtropical drying mechanism discussed above would lower the rainfall. In contrast, during the wet season (southern hemisphere summer) the tropical convection center moves southward, and the southern Amazon is within the ITCZ, thus we expect more wet-season rainfall under global warming. This seasonal dynamical mechanism is illustrated in Fig. 13.

Because the Atlantic SST gradient change persists year round, it would also reduce rainfall in the wet-season southern Amazon. In contrast, the wetter ITCZ/drier subtropics mechanism discussed above would lead to wetter wet season and drier dry season. This cancellation may explain the relatively small percentage change in precipitation during the wet season (Fig. 2b). Since the IPCC models project somewhat higher rainfall during the wet season (Fig. 2b; though with large scatter, Fig. 7), one may infer that the wetter ITCZ mechanism may have somewhat stronger influence than the change in the Atlantic SST gradient. However, during the dry season these two mechanisms work in concert, to produce a robust drier dry season (Fig. 13).

6 Discussion and conclusion

Regional climate changes predicted by previous generations of models had been highly uncertain, but the recent improvement and understanding of the IPCC climate models have permitted broad agreement in a number of key world regions (Meehl et al., 2007). This enabled us to identify a relatively robust signal and mechanisms for change in the southern Amazon, and to shed light on the important yet controversial issue of possible Amazon rainforest dieback.

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Our results suggest that an Amazon basin-wide forest dieback is unlikely based on multiple model results and an understanding of the underlying mechanisms. The model that initially suggested this possibility (Cox et al., 2000) is an end member among the 15 IPCC models we analyzed and such a possibility can not be excluded. Rather than drawing a general conclusion for the whole Amazon, we find contrasting behaviors for different parts of the Amazon. In particular, the western Amazon, the core of the rainforest, which is very wet even during the 'drier' season, will have higher rainfall which would largely counter potential adverse effects due to warming on soil moisture and vegetation.

However, the southern Amazon and central Brazil region may suffer major ecosystem degradation due to climate change. There is strong agreement that the dry season will become drier in this region in the coming century. These findings are supported by mechanistic understanding of the relevant processes (Fig. 13), including changes in the atmosphere and ocean in response to greenhouse warming:

1. The general subtropical drying under global warming and the seasonal movement of the ITCZ and associated subtropical subsidence;

2. A warmer subtropical North Atlantic Ocean relative to the South; and to lesser degree a warmer, more El Nino-like Pacific Ocean.

The resulting drier dry season interacts with land-surface hydrology and ecosystem dynamics, leading to strong ecosystem responses. The key processes include:

1. Dry season rainfall change has a disproportionately large impact on soil moisture;

2. Loss of soil moisture due to warming-enhanced evaporative demand;

3. Higher maintenance cost and possibly reduced growth at higher temperature.

One factor that might work in the opposite direction is the CO_2 fertilization effect as higher CO_2 concentration may stimulate vegetation productivity. Indeed, model sensitivity experiments (Lapola et al., 2009) show a vegetation change similar to ours without

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CO_2 fertilization effect, but an increase in Amazon vegetation when it is included. Our simulations did not include the CO_2 fertilization effect. This uncertainty has major implications for future ecosystem response in many other regions as well (Mahowald, 2007; Zeng and Yoon, 2009). Recent research appears to support a much weaker CO_2 fertilization than represented in most models especially for mature forests, though a consensus has not been reached (Hungate et al., 2003; Field, 2001; Caspersen et al., 2000; Luo et al., 2004; Korner et al., 2005).

Our analysis highlights the sensitivity of the tropical climate system to seasonal changes. The movement of the tropical convection centers leads to large seasonal variation, because a region can be influenced by the ITCZ in one season, and by the subtropical dry zone in another. Indeed, this is a basic feature of the monsoons (Lau and Zhou, 2003). As a result, climate change may manifest itself differently in different seasons, and sometimes in opposite directions. In the case of the southern Amazon, a general subtropical drying mechanism and an increased Atlantic SST gradient work together to produce a robust drier dry season, while in the wet season, these factors work in opposite directions, resulting in a wetter wet season but with less robust agreement. Similar seasonal dependence also plays a major role in the long-established ENSO-lower Amazon linkage which tends to be locked to northern winter, and in the recently highlighted Atlantic SST gradient-southern Amazon connection such as during 2005 (Yoon and Zeng, 2010; Marengo et al., 2008; Zeng et al., 2008).

The dry season rainfall decrease is relatively small in its absolute magnitude. The drying corresponds to a lengthening of the dry season by 11 days, if defined as rainfall below 1 mm d^{-1} (Fig. 6a). Yet the strong response in vegetation suggests highly nonlinear processes at play. One nonlinear process is in terrestrial hydrology as dry season precipitation is mostly used to recharge soil moisture, while a larger proportion of wet season precipitation goes into runoff. On the ecological side, the rainforest ecosystem has adapted to a short dry season by deep root water uptake, but is more susceptible to long-lasting drought. This was shown during the 2002–2005 Amazon drought (Zeng et al., 2008), and most dramatically by a multi-year precipitation-shielding experiment in

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the Amazon (Nepstad et al., 2007; Fisher et al., 2007) in which trees started to die after a few years of artificially reduced precipitation. Taking all these together, a main lesson we have learned is that tropical wet-dry ecosystems are most vulnerable to perpetual dry season drought, thus analysis of climate projections must consider the impact on seasonality in detail.

An effect that is not fully represented in most IPCC models is a possible feedback from the loss of vegetation, whether through deforestation or from climate change. Past studies on deforestation and desertification have suggested that marginal regions may be particularly sensitive to land-surface and vegetation changes (Shukla et al., 1990;Dickinson and Hendersonsellers, 1988; Charney, 1975; Zeng and Neelin, 1999). Surface degradation leads to higher albedo, reduced evaporation and other changes during the dry season, and the southern Amazon during its dry season may see further rainfall reduction when these processes are fully considered.

These climatic and ecological changes will have a dramatic effect on the landscape, biodiversity, the carbon cycle and the economy of the southern Amazon and central Brazil. Because this region is also under intense human influence, the double pressure of deforestation and climate change will put the region under heightened levels of stress in the coming years. In this subtropical region, the changes may manifest themselves as large episodic events such as fire and insect outbreaks, as opposed to gradual ecosystem transitions.

Appendix A

The IPCC models are multi-model ensembles, run with radiative forcings estimated for the twentieth century and the SRES A1B scenario for twenty-first century change. The models included are listed in the table below. Details of the model can be found at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php.

The models are interpolated onto a common 2.5°×2.5° grid. The change in climatology to the late 21st century (2070–2099 average) relative to a base period climatology

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(1961–1990 average) is averaged over the southern Amazon box (shown in Fig. 1a) is computed for all 15 models. Then, the median of the aforementioned change and that of the time series are obtained. A fractional change (measured in %) of the base period climatology is computed for each individual model and the median of the models is obtained in the same manner.

To represent the average model behavior, we define a 'median model' for each variable that takes the median of the 15 models. This process was done for each individual variable separately at each grid point. The offline VEGAS model was forced individually by the 15 model climates for variables such as precipitation and temperature for 1901–2100, and then the results are analyzed for their changes.

The terrestrial carbon model Vegetation-Global-Atmosphere-Soil (VEGAS) (Zeng, 2003; Zeng et al., 2004; Zeng et al., 2005a) simulates the dynamics of vegetation growth and competition among different plant functional types (PFTs). It includes 4 PFTs: broadleaf tree, needleleaf tree, cold grass, and warm grass. The different photosynthetic pathways are distinguished for C3 (the first three PFTs above) and C4 (warm grass) plants. Phenology is simulated dynamically as the balance between growth and respiration/turnover. Competition is determined by climatic constraints and resource allocation strategy such as temperature tolerance and height dependent shading. The relative competitive advantage then determines fractional coverage of each PFT with the possibility of coexistence. Accompanying the vegetation dynamics is the full terrestrial carbon cycle, starting from photosynthetic carbon assimilation in the leaves and the allocation of this carbon into three vegetation carbon pools: leaf, root, and wood. After accounting for respiration, the biomass turnover from these three vegetation carbon pools cascades into a fast soil carbon pool, an intermediate and finally a slow soil pool. Temperature and moisture dependent decomposition of these carbon pools returns carbon back into the atmosphere, thus closing the terrestrial carbon cycle. A fire module includes the effects of moisture availability, fuel loading, and PFT dependent resistance and captures fire contribution to interannual CO_2 variability (Zeng et al., 2005b; Qian et al., 2008). The vegetation component is coupled to land and atmo-

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sphere through a soil moisture dependence of photosynthesis and evapotranspiration, as well as dependence on temperature, radiation, and atmospheric CO_2. Unique features of VEGAS include a vegetation height dependent maximum canopy which introduces a decadal time scale that can be important for feedback into climate variability; a decreasing temperature dependence of respiration from fast to slow soil pools (Liski et al., 1999); and a balanced complexity between vegetation and soil processes. VEGAS has also been validated on interannual timescales in the tropics (Zeng et al., 2005a).

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Table 1. Summary of rainfall changes projected by the 15 IPCC AR4 models, in both the wet and dry seasons for the two regions. Boldface indicates high agreement among the models.

	Dry season (May–Sep)	Wet season (Dec–Mar)
Southern Amazon and Central Brazil (SAB)	**Drier (12 of 15 models; median change: −22%)**	Slightly wetter (9/15; median change: +5%)
Western Amazon (WA)	Slightly wetter (8/15)	**Wetter (13/15)**

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Table A1. The 15 IPCC AR4 models analyzed in this study.

Model Name	Institution	Country
CSIRO-MK3	Commonwealth Scientific and Industrial Research Organization	Australia
ECHAM5	Max Planck Institute	Germany
GFDL-CM2.0	NOAA/Geophysical Fluid Dynamics Laboratory	USA
GFDL-CM2.1	NOAA/Geophysical Fluid Dynamics Laboratory	USA
HadCM3	UKMO/Hadley Centre	UK
HadGEM1	UKMO/Hadley Centre	UK
GISS-EH	NASA/Goddard Institute for Space Studies	USA
GISS-ER	NASA/Goddard Institute for Space Studies	USA
INGV	Instituto Nazionale di Geofisica e Vulcanologia	Italy
IPSL-CM4	Institut Pierre Simon Laplace	France
MIROC-3.2-medres	Center for Climate System Research, University of Tokyo	Japan
MIROC-3.2-hires	Center for Climate System Research, University of Tokyo	Japan
MRI-CGCM2	Meteorological Research Institute	Japan
NCAR-CCSM3	National Center for Atmospheric Research	USA
NCAR-PCM1	National Center for Atmospheric Research	USA

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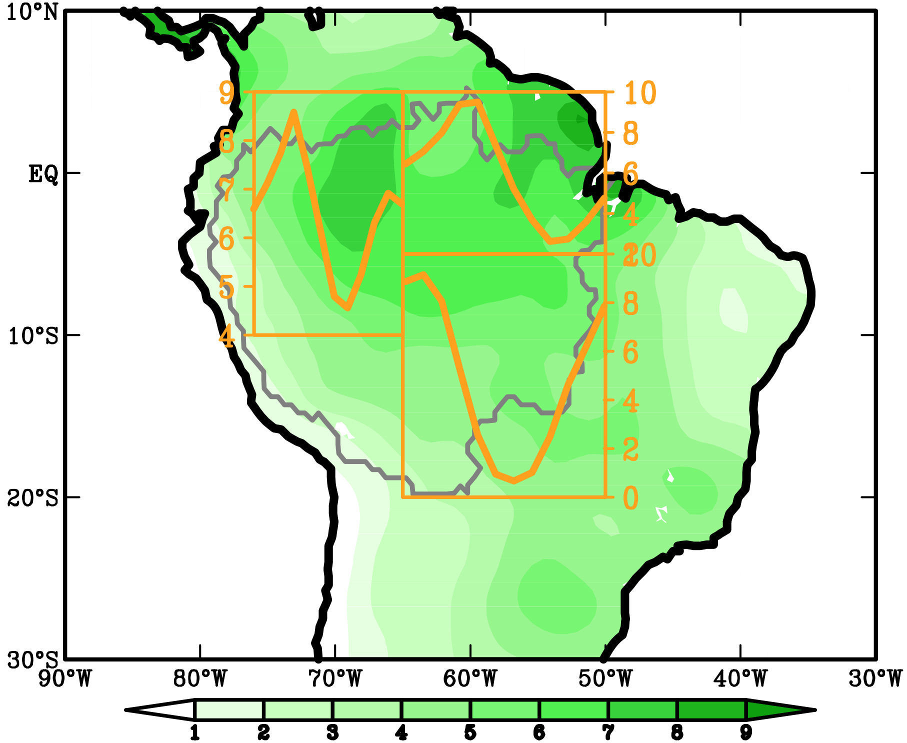

Fig. 1. nnual mean climatology of precipitation in mm d^{-1} (shading), based on satellite-gauge observations (Adler et al., 2003). The three boxes are the western Amazon (WA, 76 W–65 W and 10 S–5 N), the southern Amazon and central Brazil (SAB, 65 W–50 W, 20 S–5 S), and the eastern Amazon (EA, 65 W–50 W, 5 S–5 N), with the lines inside depicting the observed seasonal cycle in these two regions, label in mm d^{-1}.

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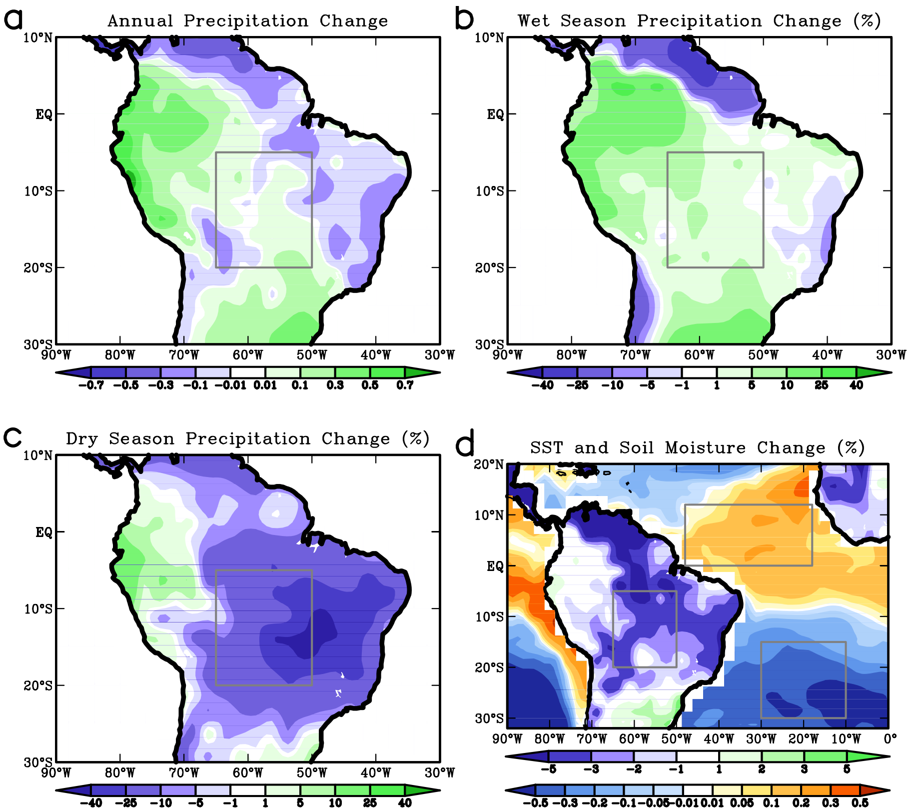

Fig. 2. Future changes in the Amazon and surrounding regions according to the median of 15 IPCC models calculated by taking the difference between the mean of the period of 2070–2099 and that of 1961–1990 for: **(a)** Annual mean precipitation (mm d^{-1}); **(b)** Wet season precipitation (%); **(c)** Dry season precipitation (%); **(d)** Annual sea surface temperature (°C) with its tropical mean removed and annual mean soil moisture (%).

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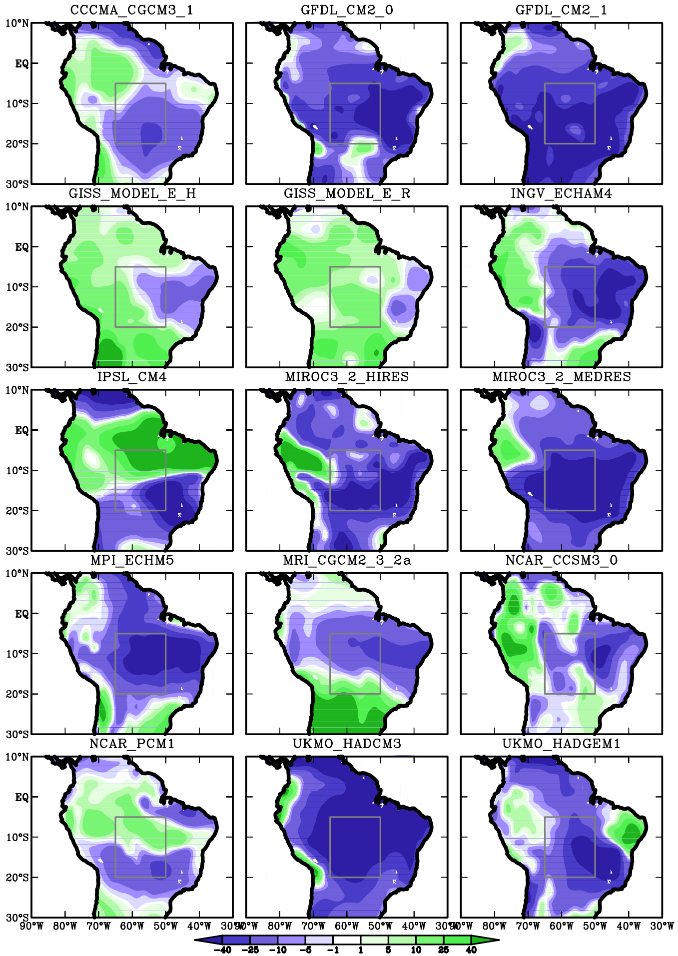

Fig. 3. Projected changes of rainfall in percentage from individual models for May–September (the SAB dry season).

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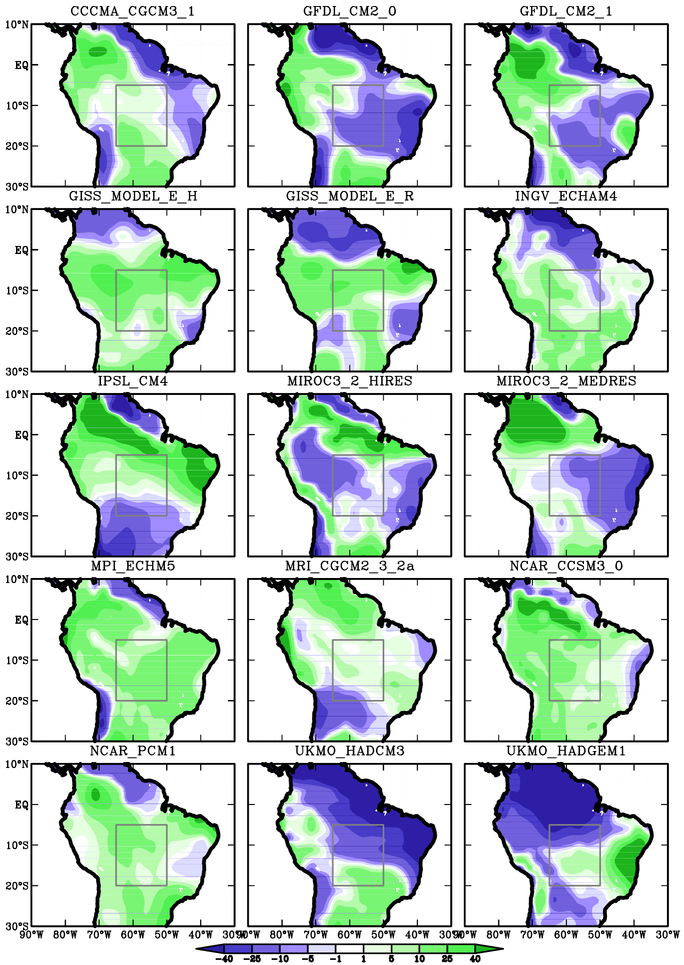

Fig. 4. As in Fig. 3, but for December–March (the SAB wet season).

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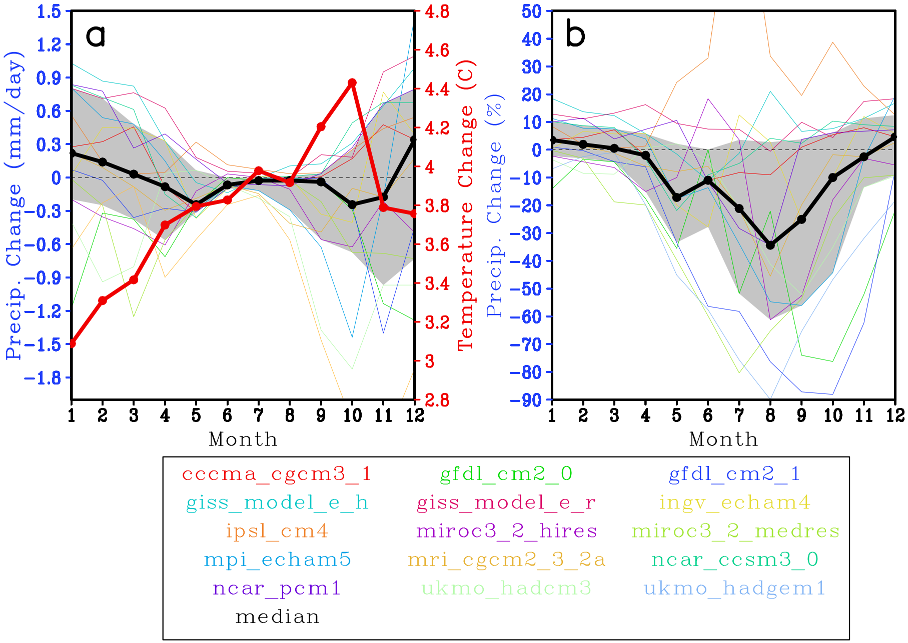

Fig. 5. Seasonal cycle of precipitation and temperature changes averaged for the SAB region from the 20th (1961–1990) to the 21st Century (2070–2099) computed at each calendar month using the 15 IPCC AR4 models. (a) Changes in temperature (°C) (red line) and precipitation (mm d^{-1}) (the median in black, individual models in color, and the 25 and 75 percentile range in grey). **(b)** Change in precipitation in percentage relative to each model's own monthly climatology. Note the large percentage decreases in precipitation in the dry season for most models, in contrast to the small percentage changes in the wet season.

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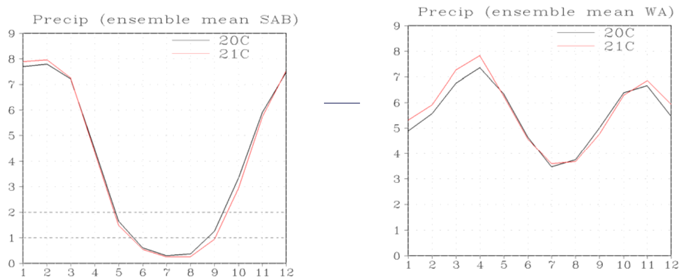

Fig. 6. Seasonal cycles of ensemble mean precipitation for the 15 IPCC models in the 20th (black) and 21st (red) century over **(a)** the SAB region and **(b)** the WA region. For the SAB, the 21st century decrease in dry season rainfall corresponds to a lengthening of the dry season (defined as rainfall less than 1 mm d^{-1}) by 11 days.

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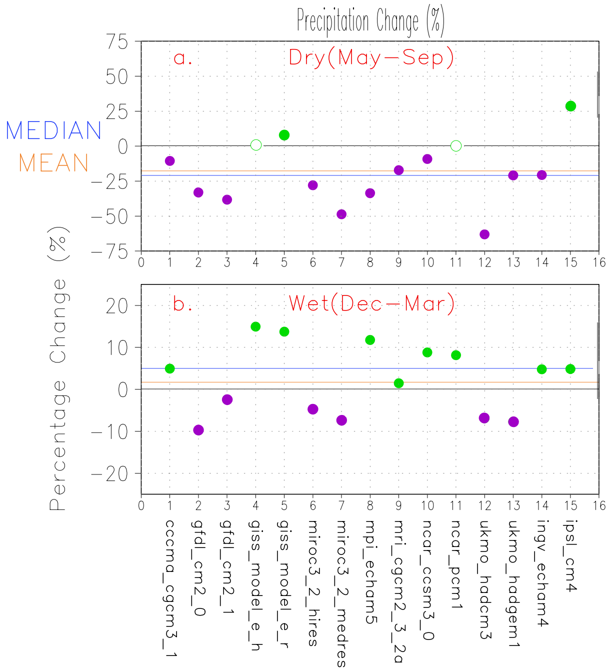

Fig. 7. Individual model precipitation change from the 20th to 21st century averaged over the SAB region for the dry season **(a)** and wet season **(b)**. The majority of models suggest a drying of the dry season. The median of these models is shown by the blue line, and the mean in orange. Green dots denote an increase in precipitation, purple dots a decline. Models suggesting a change close to zero have open circles.

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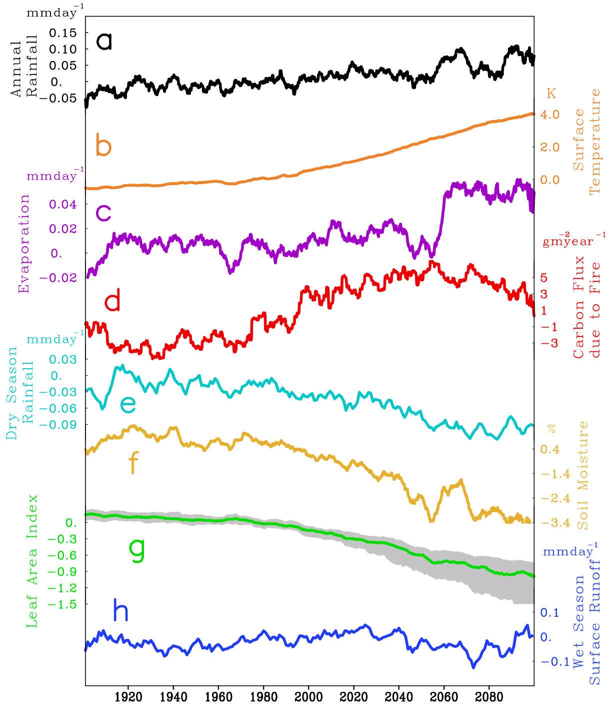

Fig. 8. A time series plot showing the changes in **(a)** Annual precipitation (mm d^{-1}), **(b)** Surface temperature (°C), **(c)** Evaporation (mm d^{-1}), **(d)** Fire carbon flux to atmosphere (g m^{-2} y^{-1}), **(e)** Dry season rainfall (mm d^{-1}), **(f)** Percentage change in soil moisture (VEGAS), **(g)** Leaf area index with shading for 25 and 75 percentile of models, and **(h)** Wet season runoff (mm d^{-1}), all as projected by the median change of the IPCC models for the SAB region from 1900–2100.

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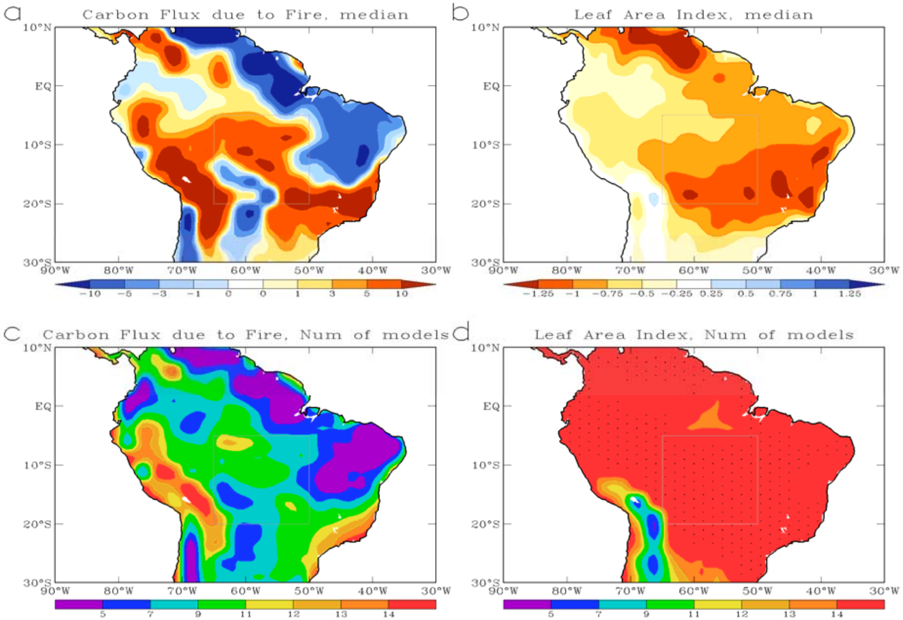

Fig. 9. Annual changes of ecosystem variables from the 20th Century (1961–1990) to the 21th Century (2070–2099) for **(a)** Carbon release due to fire ($g\,m^{-2}\,y^{-1}$), **(b)** LAI, from the median of the VEGAS model driven by the 15 IPCC models; and the number of models that project **(c)** an increase in fire, **(d)** a decrease in LAI (all 15 models show decrease in the dotted regions).

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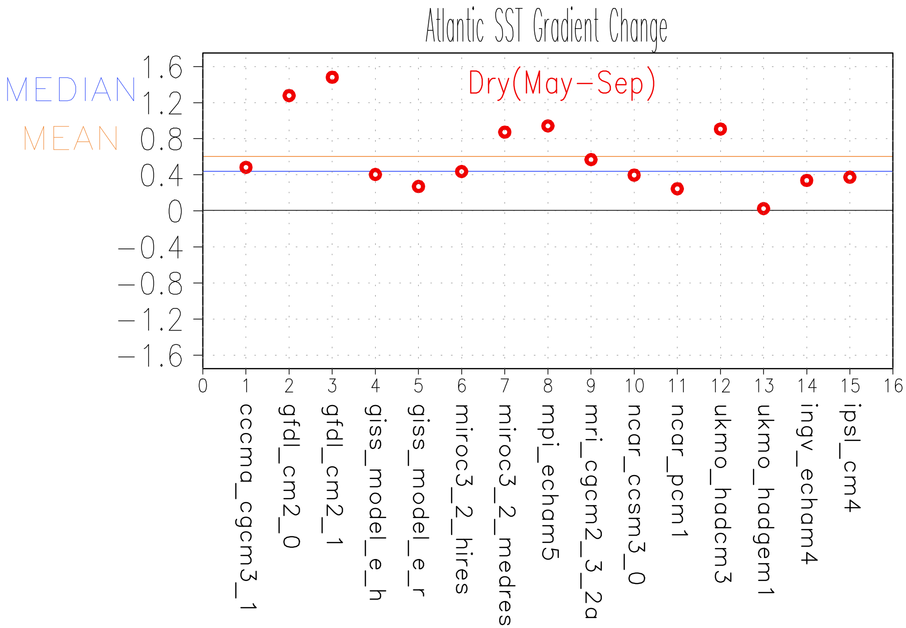

Fig. 10. Individual model results for change in the Atlantic SST gradient over the next century for the dry season (May–September). The North Atlantic is defined as (EQ-12° N, 18° W–48° W), the south is defined as (15° S–30° S, 10° W–30° W). The boxes can be viewed on Fig. 2d. The North-South SST gradient increases for all models. The median change in temperature gradient is shown in blue, and mean in orange.

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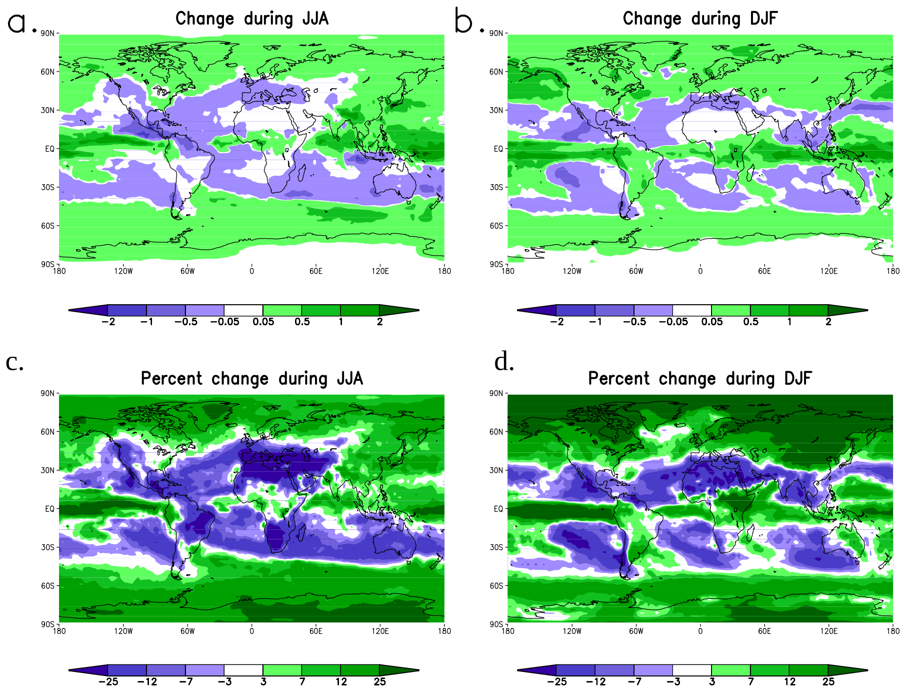

Fig. 11. IPCC model median change in precipitation (mm d^{-1}) from the 20th to 21st century for the northern summer (JJA) and winter (DJF) seasons: **(a)** Net change (mm day^{-1}) in June, July and August (JJA). **(b)** Net change (mm day^{-1}) in December, January and February (DJF). **(c)** Percentage change in JJA. **(d)** Percentage change in DJF. Note (i) the expansion of the subtropical dry zones, which coincides with reduced Amazon rainfall during northern summer, and (ii) the general strengthening of the ITCZ, which increases Amazon rainfall during the northern winter.

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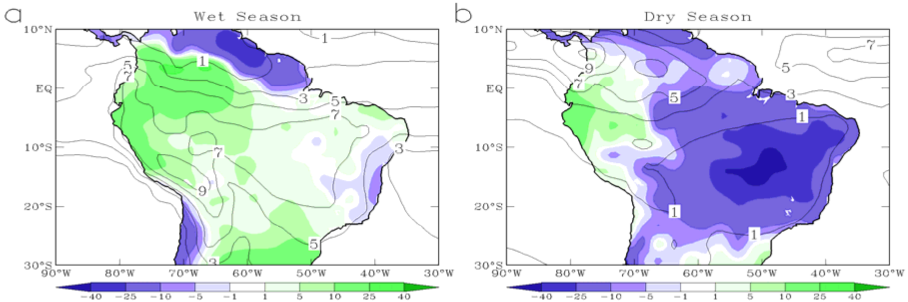

Fig. 12. A graphic displaying 20th century rainfall in (mm d^{-1}) in contours, with percentage change in **(a)** SAB wet season and **(b)** SAB dry season precipitation from the 20th to the 21st century overlain with shading. (a) Wet season change: the region where contours are in close proximity is indicative of the position of the ITCZ during the wet season. Note that the precipitation change is positive in the ITCZ region, and negative north of the ITCZ in the subtropical dry zone. (b) Dry season change: The large purple region shows that in the future the subtropical dry zone (which dominates Brazil during the dry season) will expand in spatial area, and become more intense, leading to a general drying of the region.

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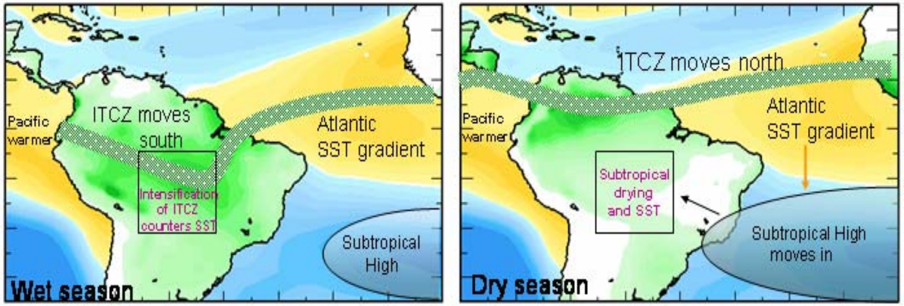

Fig. 13. A schematic diagram showing the two mechanisms under global warming (general subtropical drying, stronger Atlantic SST gradient and eastern Pacific warming) that may work in concert to produce a robust drier dry season in the southern Amazon and central Brazil (boxed area), but act in opposite directions in the Amazon wet season, leading to relatively small change. Background colors indicate climatological rainfall on land (green), the subtropical high pressure system (grey), and median IPCC model projected late 21st century SST with tropical mean removed (light brown and blue).

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