EARTH Interactions

Will Amazonia Dry Out? Magnitude and Causes of Change from IPCC Climate Model Projections

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ABSTRACT: The Amazon rain forest may undergo significant change in response to future climate change. To determine the likelihood and causes of such changes, the authors analyzed the output of 24 models from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) and a dynamic vegetation model, Vegetation–Global–Atmosphere–Soil (VEGAS), driven by these climate output. Their results suggest that the core of the Amazon rain forest should remain largely stable because rainfall in the core of the basin is projected to increase in nearly all models. However, the

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periphery, notably the southern edge of Amazonia and farther south into central Brazil (SAB), is in danger of drying out, driven by two main processes. First, a decline in precipitation of 11% during the southern Amazonia's dry season (May–September) reduces soil moisture. Two dynamical mechanisms may explain the forecast reduction in dry season rainfall: 1) a general subtropical drying under global warming when the dry season southern Amazon basin is under the control of subtropical high pressure and 2) a stronger north–south tropical Atlantic sea surface temperature gradient and, to a lesser degree, a warmer eastern equatorial Pacific. The drying corresponds to a lengthening of the dry season by approximately 10 days. The decline in soil moisture occurs despite an increase in precipitation during the wet season, because of nonlinear responses in hydrology associated with the decline in dry season precipitation, ecosystem dynamics, and an increase in evaporative demand due to the general warming. In terms of ecosystem response, higher maintenance cost and reduced productivity under warming may also have additional adverse impact. Although the IPCC models have substantial intermodel variation in precipitation change, these latter two hydroecological effects are highly robust because of the general warming simulated by all models. As a result, when forced by these climate projections, a dynamic vegetation model VEGAS projects an enhancement of fire risk by 20%–30% in the SAB region. Fire danger reaches its peak in Amazonia during the dry season, and this danger is expected to increase primarily because of the reduction in soil moisture and the decrease in dry season rainfall. VEGAS also projects a reduction of about 0.77 in leaf area index (LAI) over the SAB region. The vegetation response may be partially mediated by the CO_2 fertilization effect, because a sensitivity experiment without CO_2 fertilization shows a higher 0.89 decrease in LAI. Southern Amazonia is currently under intense human influence as a result of deforestation and land-use change. Should this direct human impact continue at present rates, added pressure to the region's ecosystems from climate change may subject the region to profound changes in the twenty-first century.

KEYWORDS: Climate change; Amazonia; Drought

1. Introduction

A coupled climate–carbon cycle model study projected a major dieback of the Amazon rain forest toward the end of this century under global warming, with much of the Amazon forest being replaced by savanna or C_4 grasses (Betts et al. 2004; Cox et al. 2000; Cox 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 rain forest 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 rain forest by 2050 (Soares-Filho et al. 2006). A possible susceptibility to human-induced climate change would impose additional danger (Malhi et al. 2008). Because of the potential for large changes in carbon stocks in this region, the Amazon rain forest 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 widespread conversion of rain forest to savanna or grasslands (Cowling and Shin 2006; Schaphoff et al. 2006), although these studies did not use a coupled climate–vegetation model, thus not including presumably positive vegetation feedback (Malhi et al. 2009). Additionally, instrumental and proxy records show that the Amazon rain forest was relatively stable throughout the twentieth century and in the geological past, such as during glacial times and the Holocene warm period (Baker et al. 2004; Bush and Silman 2004; Malhi and Wright 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 Amazonia will become wetter in the future: It is believed that the intertropical convergence zone (ITCZ), which encompasses the atmospheric convection center in the Amazon basin, will become stronger in the future because of a more vigorous hydrological cycle driven by global warming (Held and Soden 2006). Thus, one may expect more rainfall over the Amazon basin. On the ecosystem side, the large rainfall amount of over 2000 mm yr^{-1} in the core of the Amazon basin supplies abundant water. Because of the frequent rainfall and cloudy sky, it has been suggested that the limiting factor for forest growth in Amazonia is sunlight and not water, so that even a decrease in precipitation may not necessarily have adverse impacts on the ecosystem (Huete et al. 2006; Nemani et al. 2003; Saleska et al. 2003), although this notion has not been widely accepted either.

Another factor that has led to confusion is that the Amazon basin is not defined in the same way across all studies. Process-level mechanisms suitable for one part of the Amazon basin are sometimes applied to other parts of the basin without sufficient caution. Several different factors influence precipitation patterns in different parts of Amazonia, and it is important to note these regional differences. Rainfall in Amazonia 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 in the core of the rain forest [western Amazonia (WA), broadly represented by a box enclosing 10°S–5°N and 76°–65°W in Figure 1] has double maxima as the sun crosses the equator twice a year, and the ITCZ moves along with it. In contrast, southern Amazonia and central Brazil (SAB; a box shown in Figure 1: 20°–5°S, 65°–50°W) has its rainy season (December–March) in Northern Hemisphere winter with rainfall higher than 6 mm day^{-1} and a dry season (May–September) with rainfall lower than 1 mm day^{-1} as the ITCZ and associated land convection center move back and forth following solar heating (Figures 1, 13). Although WA also has lower rainfall during May–September, it is still as high as 4 mm day^{-1}, meaning there is no real dry season in this region. Further, rainfall never dips below 2 mm day^{-1} in the eastern part, lower Amazonia (EA). Thus, one may reason that water stress may be an important issue affecting rain forest health in the SAB region, but it is not likely to be as critical in WA and EA.

Climate variability such as sea surface temperature (SST) changes in the eastern Pacific Ocean associated with El Niño–Southern Oscillation (ENSO) are known to have a strong impact on Amazonia, but the center of the impact tends to be in EA (Ropelewski and Halpert 1987). Indeed, the Hadley Centre model simulates an initial drying in lower Amazonia, akin to the typical El Niño response, consistent with the fact that the Hadley Centre model projects a strong perpetual El Niño–like state under global warming (Betts et al. 2004; Cox et al. 2004). This initial drying progresses farther 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 precipitation in southern

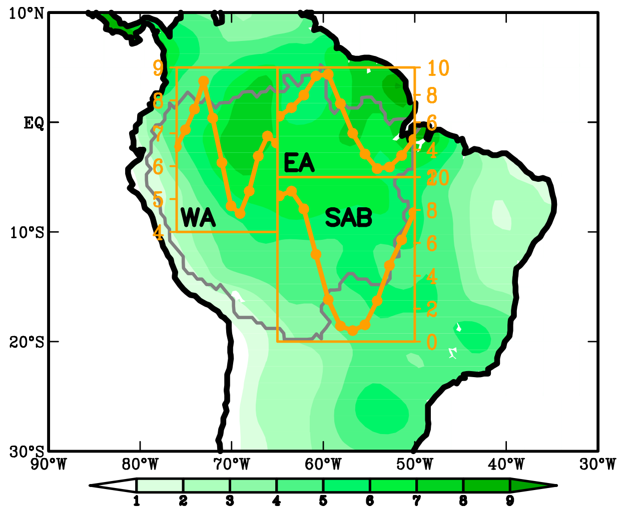

Figure 1. Annual-mean climatology of precipitation in mm day^{-1} (shading) based on satellite gauge observations (Adler et al. 2003). The three boxes are western Amazonia (10°S–5°N, 76°–65°W), eastern Amazonia (5°S–5°N, 65°–50°W), and southern Amazonia and central Brazil (20°–5°S, 65°–50°W), with the lines inside depicting the observed seasonal cycle (from January to December) in these regions, labeled in mm day^{-1}. This work focuses on the SAB region.

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

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Meehl et al. 2007) climate simulations under specified emissions scenarios provide an opportunity to examine the issue of future change in Amazonia with multiple models. The annually averaged global analysis from the IPCC AR4 shows little change in net rainfall in the Amazon basin in the twenty-first century (Meehl et al. 2007) (Figures 2a, 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 Amazonia. 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 nonlinearity 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 Amazonia (Phillips et al. 2009; Zeng et al. 2008), so dry season precipitation may have nonlinear impacts on ecosystem health. Such hypotheses largely motivated this study.

Here we analyze 24 IPCC AR4 models for their projected changes in precipitation, surface air temperature, soil moisture, SST, and other relevant climate variables for the Amazon basin and surrounding regions. We will focus our

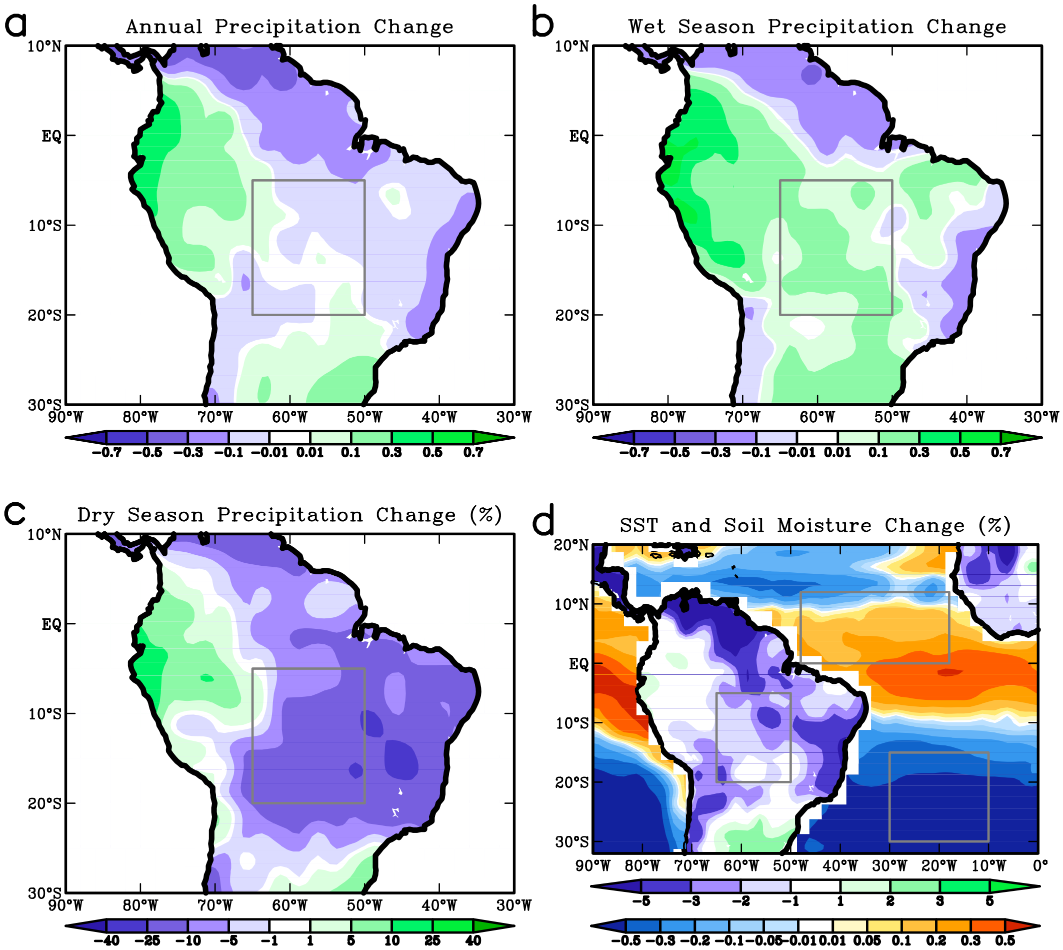

Figure 2. Future changes in the Amazon basin and surrounding regions according to the median of 24 IPCC models calculated by taking the difference between the mean of the period of 2070–99 and that of 1961–90 for (a) annual-mean precipitation (mm day^{-1}), (b) wet season precipitation (mm day^{-1}), (c) dry season precipitation (%), and (d) annual SST (°C) (with tropical mean removed) and annual-mean soil moisture (%).

discussion on the behavior of the median of the individual changes for each model projection while showing some individual model results and intermodel 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 hydroecosystem 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.

2. Data and models

The IPCC models used in this study are each multimodel ensembles. Each model was run from 1901 to 2099. Estimated radiative forcings were used to drive the models for the twentieth century. The Special Report on Emissions Scenarios (SRES) A1B scenario was used to simulate twenty-first century climate. The A1B emissions scenario was selected because it is a fairly representative average of the different emission scenarios conducted by the IPCC and it is close to the current pace of anthropogenic greenhouse gas (GHG) emissions (Raupach et al. 2007). Scholze et al. (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. All the models have both precipitation and surface air temperature for the twentieth century and the A1B emissions scenarios were analyzed for the 24 models listed in the appendix. The monthly model output was interpolated onto a common $2.5° \times 2.5°$ grid. Change in ecosystem variables from the late-twentieth-century climatology (1961–90 average) to the late-twenty-first century (2070–99 average) was computed. In this study, we focus on two regions, the core of the Amazon rain forest (WA: 10°S–5°N, 76°–65°W) and SAB (20°–5°S, 65°–50°W); these regions are designated with boxes in Figure 1. We also analyzed EA and found that the predicted precipitation change is similar in magnitude to the SAB region. An independent analysis (Malhi et al. 2009) found similar results to ours for the EA. Because the EA is climatologically wetter (similar to WA) than the SAB region, the vulnerability to biome change there should be lower than in the SAB, 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 (1961–90) and the future climatology (2070–99). 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 were 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 twentieth century to the twenty-first century, not the absolute value of the variable.

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, whereas not all models do an equally good job in reconstructing the twentieth-century climatology of Amazonia. In fact, some researchers have attempted to develop metrics that assign different weight to the GCMs based upon their ability to reproduce the climatology of the twentieth 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 because those models that do a better job in simulating the climatology of the twentieth century tend to forecast a reduction in precipitation in the twenty-first 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 intermodel 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, and each region separately.

The dynamic vegetation and terrestrial carbon cycle model Vegetation–Global–Atmosphere–Soil (VEGAS; see appendix) was forced individually by the 24 model climates for variables such as precipitation and temperature from 1901 to 2099, preceded by a spinup using each climate model's first year output for 300 years. This experiment includes the CO_2 fertilization effect following the A1B scenario. To further separate climate and CO_2 fertilization effects, sensitivity experiments without CO_2 fertilization effect were performed. The monthly climate model output was interpolated to daily time steps to drive the vegetation model. 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 of whether the Amazon rain forest will dry out in the future. When comparing the model-simulated rainfall for 2070–99 to that of 1961–90, median annual rainfall is projected to increase across much of the Amazon basin and South America (Figure 2a). This change is dominated by moderately increased rainfall during the SAB's wet season (December–March) (Figure 2b). However, during the SAB's dry season (May–September), the models show a clear decrease in rainfall in southern Amazonia, extending into central Brazil, northeastern Brazil (Nordeste), and neighboring countries (Figure 2c). In particular, the following models show a greater than 25% decline in precipitation inside the SAB region during the dry season (Figure 3): Geophysical Fluid Dynamics Laboratory Climate Model version 2.0 (GFDL CM2.0); GFDL CM2.1; Model for Interdisciplinary Research on Climate 3.2, medium-resolution version [MIROC3.2(medres)]; MIROC3.2(hires); Max Planck Institute (MPI) ECHAM5; third climate configuration of the Met Office (UKMO) Unified Model (HadCM3); Hadley Centre Global Environmental Model version 1 (HadGEM1); Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled General Circulation Model, version 3.1 T63 (CGCM3.1-T63); Commonwealth Scientific and Industrial Research Organisation Mark version 3.0 (CSIRO Mk3.0); and Institute of Numerical Mathematics Coupled Model, version 3.0 (INM-CM3.0). Only six models predict an increase in rainfall during this time of the year: Goddard Institute for Space Studies Model E-R (GISS-ER); L'Institut Pierre-Simon Laplace (IPSL) Coupled Model, version 4 (CM4); Institute of Atmospheric Physics (IAP) Flexible Global Ocean–Atmosphere–Land System Model gridpoint version 1.0 (FGOALS-g1.0); and CSIRO Mk3.5. The remaining models fall between these two extremes. In contrast, when the models are averaged, western Amazonia tends to have more rainfall during both the wet and dry seasons. This is especially true in the SAB's wet season (Figure 4). We thus focus our analysis on the southern Amazon basin and the central Brazil region, which appears to be more vulnerable.

Temperature in the SAB region is projected to increase by 3°–4°C by the late twenty-first century, relative to the late twentieth century, with the largest increase occurring at the end of the dry season (Figure 5a). Regarding rainfall, the IPCC models suggest that the region will become wetter by more than 0.1 mm day^{-1} on an annual average basis (Figures 5a, 8a). However, the increase in precipitation is not spread equally throughout the year. The median change is dominated by a wet season increase of over 0.2 mm day^{-1} (Figure 5a). Conversely, during the driest time of the year in SAB, precipitation is

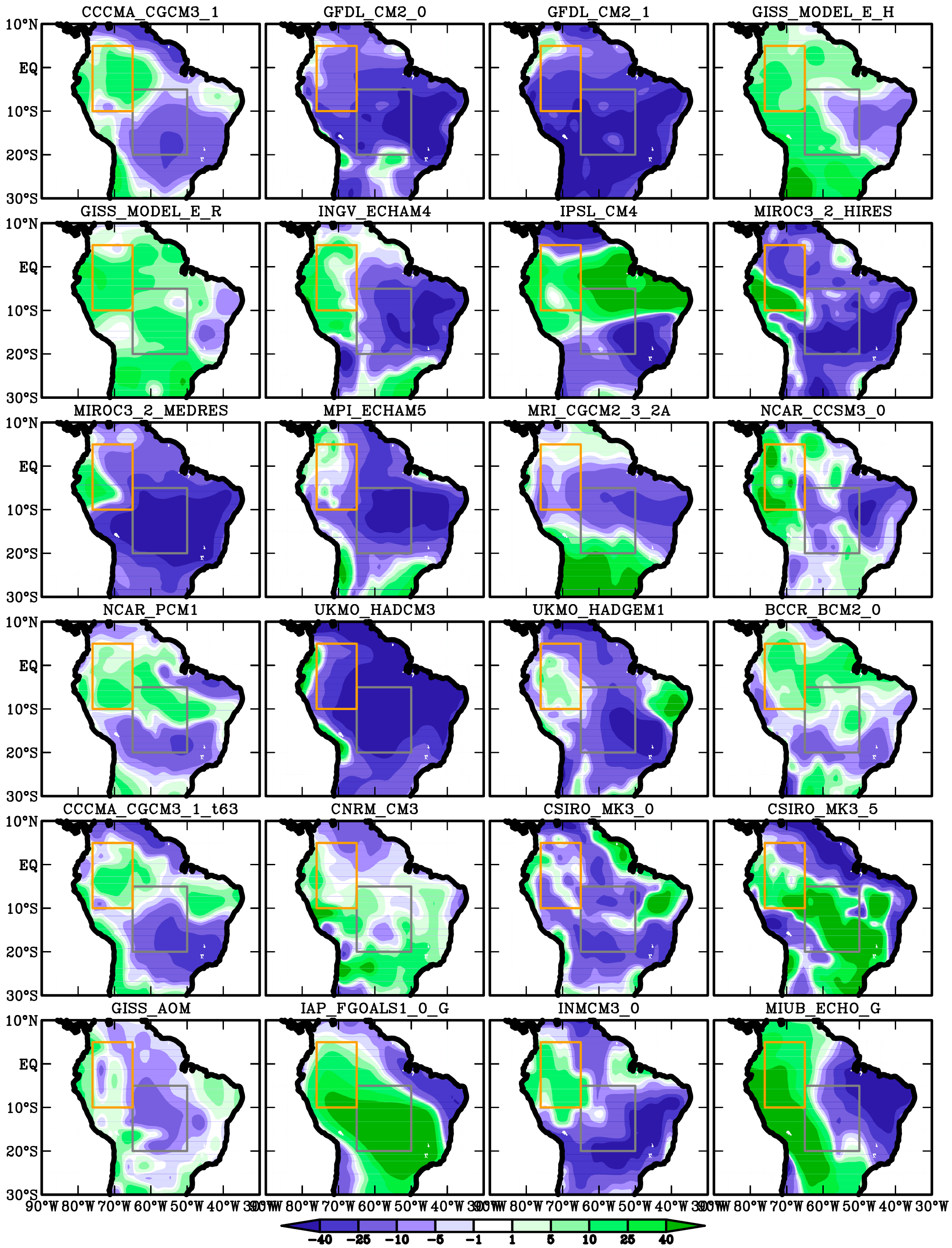

Figure 3. Projected changes of rainfall (percent) from individual models for May–September (the SAB dry season). The gray box shows the SAB as defined in Figure 1.

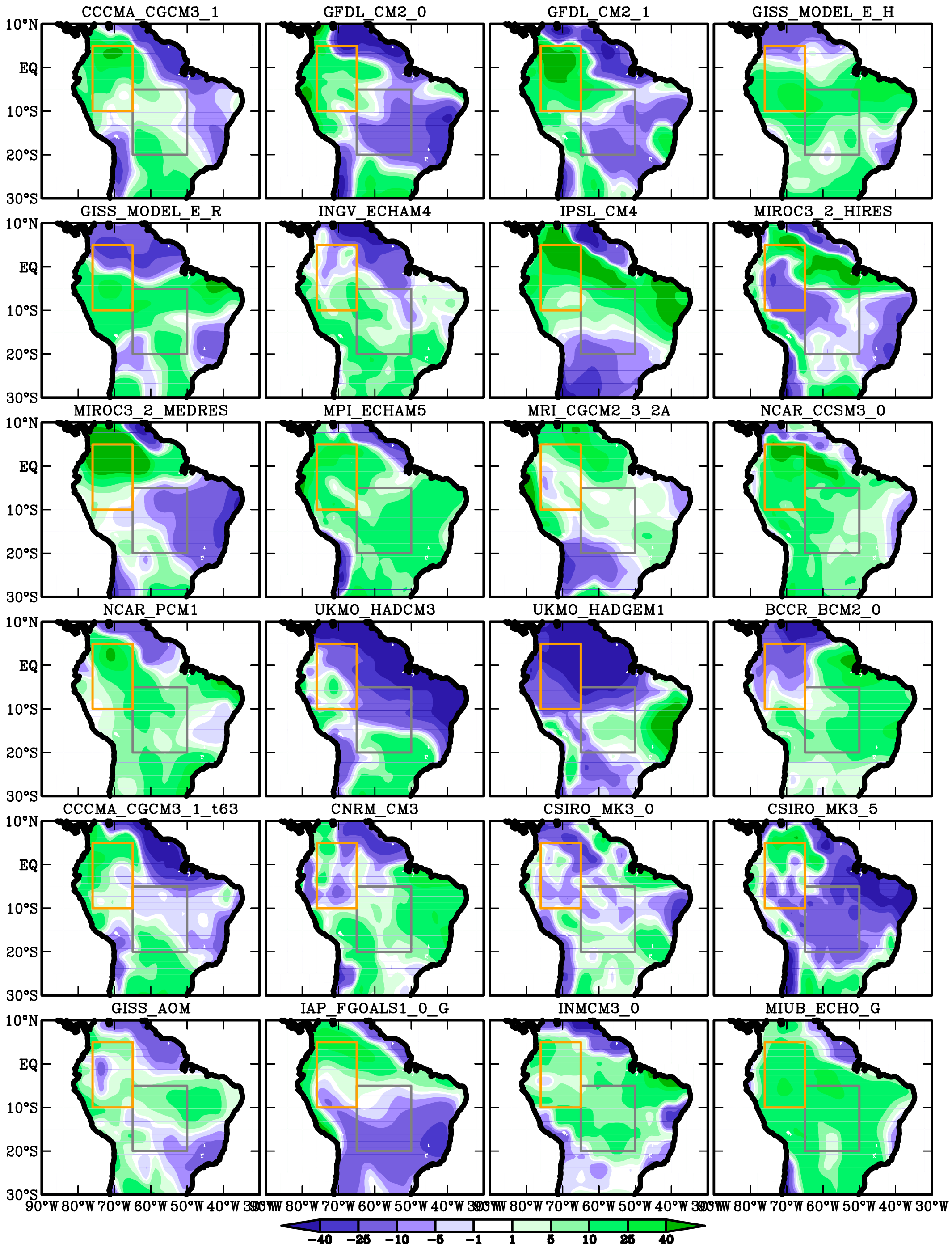

Figure 4. As in Figure 3, but for December–March (the SAB wet season). The gray box shows the SAB region.

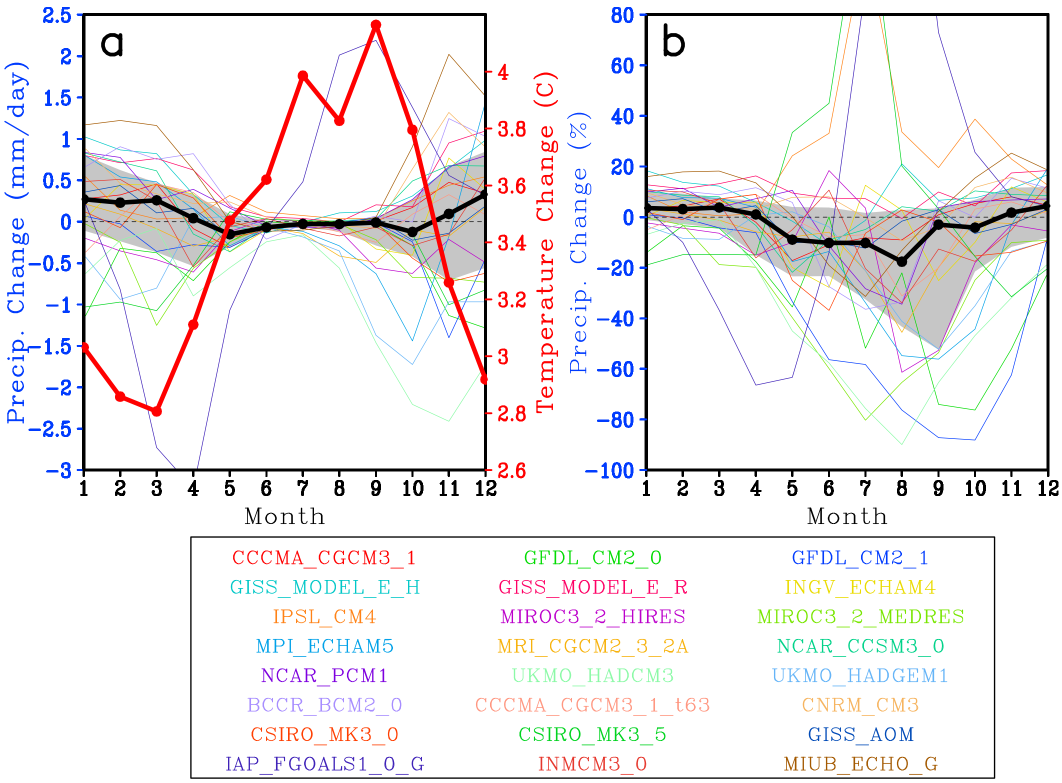

Figure 5. Seasonal cycle of precipitation and temperature changes averaged for the SAB region from the twentieth (1961–90) to the twenty-first century (2070–99) computed for each calendar month using the 24 IPCC AR4 models. (a) Changes in temperature (°C) (red line) and precipitation (mm day^{-1}) (the median in black, individual models in color, and the 25th- and 75th-percentile range in gray). (b) Change in precipitation (percent) 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.

projected to decrease, but by less than 0.1 mm day^{-1}. Interestingly, the maximum decrease occurs in the transition months of May and October, and the driest months of June–August (JJA) have miniscule reduction because the climatological rainfall is already very low. Indeed, some models have a twentieth-century climatological dry season that is significantly drier than observations (not shown). As a result of the decline in precipitation during the transitional months, there is a lengthening of the dry season by about 10 days (where the dry season is defined as the number of days during which precipitation is less than 1 mm day^{-1} on average) (Figure 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 relatively drier months (Figure 6b) and rainfall is expected to increase during the wet season.

At first glance, this result would suggest that there is no need to worry about a drying of the Amazon basin. However, the dry season rainfall reduction becomes

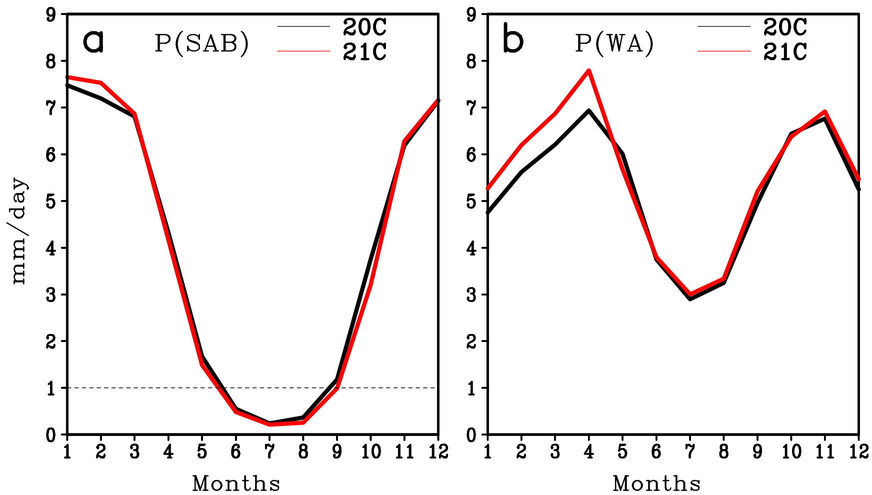

Figure 6. Median seasonal cycles of precipitation for the 24 IPCC models in the twentieth (black) and twenty-first (red) centuries over the (a) SAB and (b) WA regions. The abscissa is month of the year, whereas the ordinate is precipitation in mm day^{-1}. For the SAB, the twenty-first-century decrease in dry season rainfall corresponds to a lengthening of the dry season (defined as rainfall less than 1 mm day^{-1}, marked as dashed line) by approximately 10 days.

prominent when viewed as a percentage change. The median change suggests that dry season SAB rainfall will decrease by 10.5%, with some areas declining by as much as 40% (Figure 2c). Out of the 24 models, 16 show significant rainfall reduction in the dry season, 4 have little change, and 4 show small to significant increases (Figure 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: 14 models become wetter, whereas 8 become drier (Figure 7b). Thus, the most robust rainfall changes appear to be a "drier dry season" for the SAB region and a "wetter wet season" for both SAB and WA regions, as summarized in Table 1. We now analyze how this seasonally dependent change in rainfall interacts with nonlinear dynamics to generate major hydroecosystem 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 (Figure 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 we expect to see in the coming century will drain as runoff (Figure 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 used by the ecosystem; thus, a decline in dry season rainfall 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 Amazonia would significantly increase evaporative demand, regardless of precipitation change. More evaporation by itself tends to reduce soil moisture. The fact that the models project a slight increase in evaporation (Figure 8c), despite the decrease in soil moisture (Figure 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 twenty-first century, the VEGAS model, forced by the IPCC climate model projections, shows a decrease in soil moisture of 8%, a decrease of leaf area index (LAI) by about 1.0 (12.6%), and an increase in land–atmosphere carbon flux due to fire of about 27.2% (Figure 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 (Phillips et al. 2009; Zeng et al. 2008). A similar nonlinearity exists with respect to fire risk. Fire is most prevalent in the SAB near the end of the dry season (Aragao et al. 2008; Cochrane et al. 1999). The SAB is at heightened risk for fire at this time of the year because of several factors, including lower atmospheric humidity, strong winds, extreme solar radiation, and decreased soil moisture. In this analysis, we focused on how changes in soil moisture affect the frequency and intensity of fire risk in the region and found that 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, because the increased rainfall occurs during a time of year when little fire occurs anyway. Changes in humidity, wind speed, and direct solar radiation in the twenty-first century may also have an impact on the amount of fire in this region but were not included in this analysis.

The spatial distribution (Figure 9) of the twenty-first-century vegetation-related changes show widespread decrease in LAI beyond the area with a drier dry season and, needless to say, even greater decrease in LAI for the area with lower annual-mean precipitation (cf. Figure 2). LAI is projected to decrease by over 0.5 in southern Amazonia and by more than 0.75 in central Brazil in the twenty-first century. The results here support those from Malhi et al. (Malhi et al. 2009), which show the Amazon rain forest may tend toward a seasonal forest climate under climate change. 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 an increased incidence of fire by the end of the twenty-first century. Alarmingly, increased fire risk occurs high into the Andes from Bolivia to Peru and Colombia, apparently driven by the reduced soil moisture (Figure 2d). An increase in LAI is seen in a small area of the Bolivian altiplano (Figure 9b), although there is

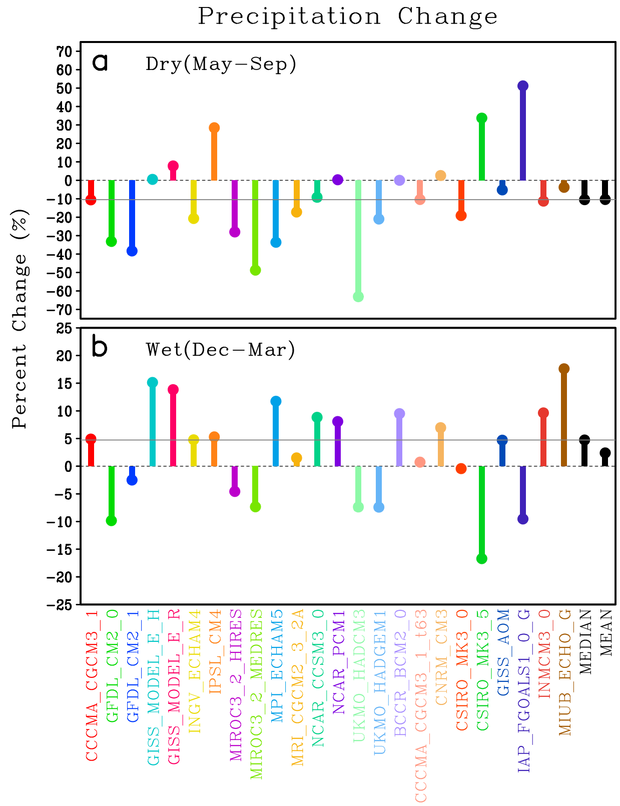

Figure 7. Individual model precipitation change from the twentieth century to the twenty-first century averaged over the SAB region for the (a) dry and (b) wet seasons. The majority of models suggest a decline in rainfall during the dry season. The color used for each model is consistent with Figure 5. The median changed is displayed with the gray line.

some disagreement among the models regarding this result (Figure 9d). The increase in LAI in this region is probably due to the warmer temperatures, because vegetation growth in cold, high, mountainous regions is often limited by temperature, not rainfall. Interestingly, this added growth provides additional fuel for fire (Figure 9a), although 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, Lund–Potsdam–Jena (LPJ) (Scholze et al. 2006). Our analysis of the nonlinear

Table 1. A summary of rainfall changes projected by the 24 IPCC AR4 models, in both the wet and dry seasons for the two regions. Boldface indicates high agreement among the models.

	Dry season (May–September)	Wet season (December–March)
SAB	**Drier (16 of 24 models; median change: −10.5%)**	Slightly wetter (14 of 24 models; median change: +4.7%)
WA	Slightly wetter (13 of 24 models)	**Wetter (17 of 24 models)**

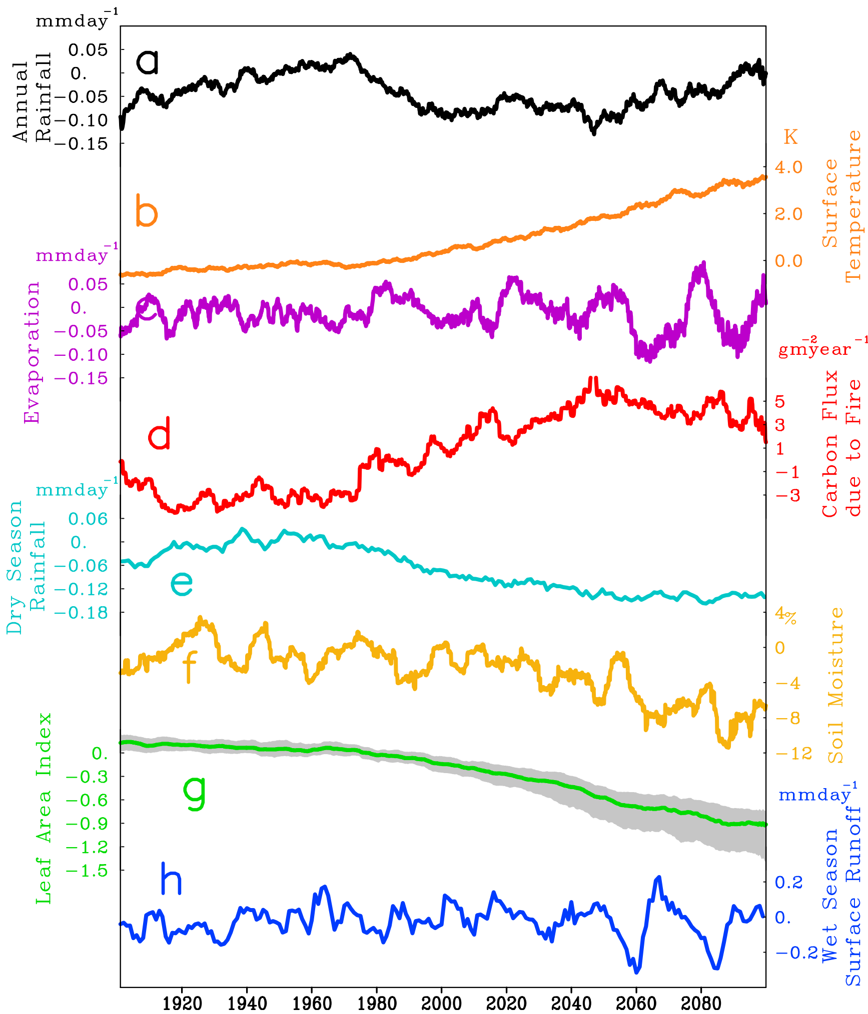

Figure 8. A time series plot showing the changes in (a) annual precipitation (mm day^{-1}), dominated by wet season change; (b) surface temperature (°C); (c) evaporation (mm day^{-1}); (d) fire carbon flux to the atmosphere (g m^{-2} yr^{-1}); (e) dry season rainfall (mm day^{-1}); (f) percentage change in soil moisture (VEGAS); (g) LAI with shading for the 25th and 75th percentiles of models; and (h) wet season runoff (mm day^{-1}), as projected by the median change of the 24 IPCC models for the SAB region from 1901 to 2099.

hydroecological response offers an explanation for the major potential changes in the SAB 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 changes in dry season precipitation on the vegetation in the SAB. The question naturally arises as to the robustness and mechanisms responsible for such changes. The fact that rainfall

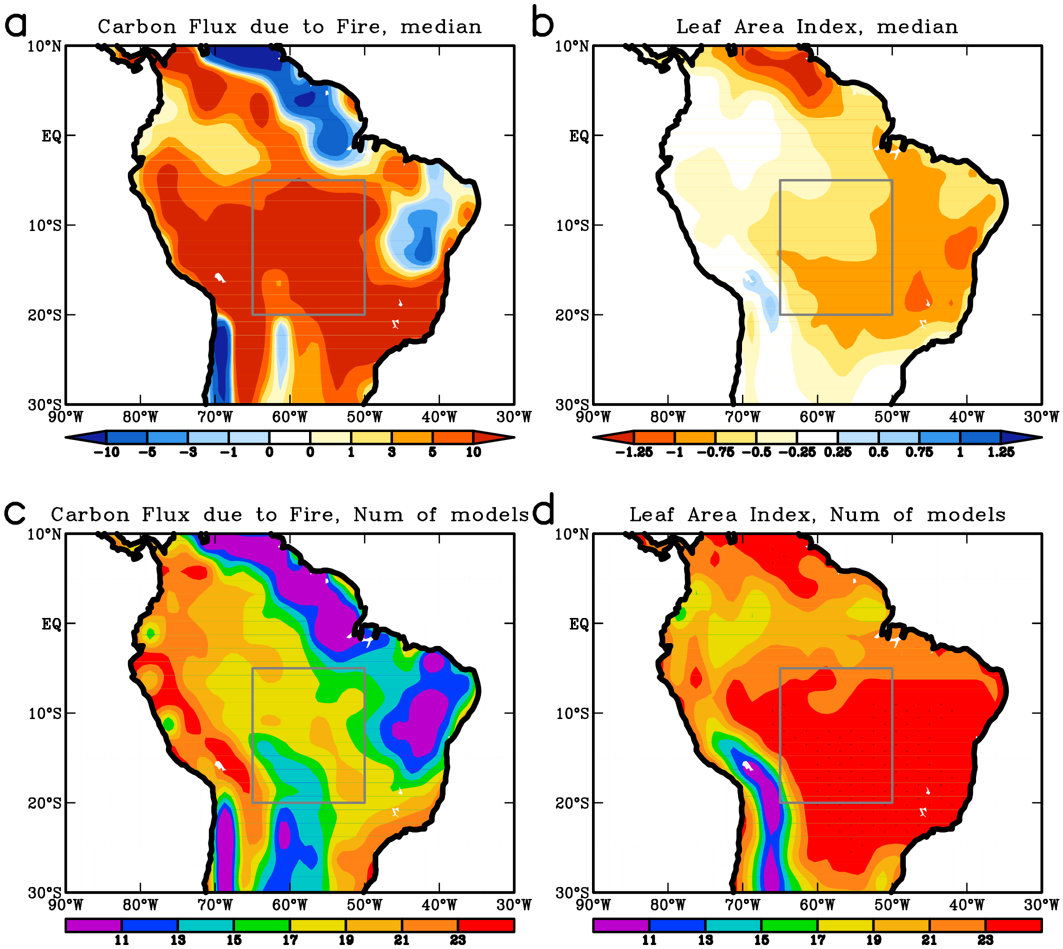

Figure 9. Annual changes of ecosystem variables from the twentieth century (1961–90) to the twenty-first century (2070–99) for (a) carbon released due to fire (g m^{-2} yr^{-1}); (b) LAI, from the median of the VEGAS model driven by the 24 IPCC models; and the number of models that project (c) an increase in fire carbon flux and (d) a decrease in LAI (all 24 models show decrease in the dotted regions).

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 climate change the equatorial Pacific Ocean will become more El Niño–like; that is, the eastern equatorial Pacific will be permanently warmer relative to the western Pacific than it was during the twentieth century, corresponding to a weakening of the Walker circulation (Meehl et al. 2005; Vecchi et al. 2006). It has long been known that warm SST anomalies associated with El Niño suppress rainfall over Amazonia, particularly the lower Amazon basin (Ropelewski and Halpert 1987). A similar warm SST anomaly, relative to background warming, is clearly seen in the median of the

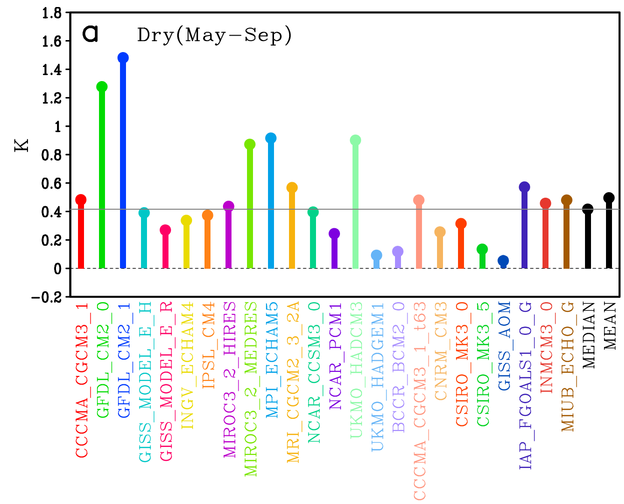

Figure 10. Individual model results for the change in the Atlantic SST gradient over the next century for the dry season (May–September). The North Atlantic is defined as (equator–12°N, 18°–48°W), and the south is defined as (15°–30°S, 10°–30°W). The boxes can be seen in Figure 2d. The north–south SST gradient increases for all 24 models. The median change in temperature gradient is shown by the gray line.

IPCC models (Figure 2d) and could contribute to the reduced rainfall over the Amazon basin, especially in some models (Cox et al. 2000). However, El Niño–induced rainfall change tends to be concentrated in lower Amazonia (Ropelewski and Halpert 1987; Zeng et al. 2008) and indeed the drying along the northeast coast of South America (Figure 2a) may be in part a result of this, but the main explanation for a drier SAB must lie somewhere else.

The reduced dry season rainfall may be more related to changes in the tropical Atlantic Ocean (Figure 2d). The change in the Atlantic SST gradient is very robust as all 24 models show an increase in the North Atlantic to South Atlantic temperature gradient (Figure 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 (Cox et al. 2008; Marengo et al. 2008; Zeng et al. 2008). The subsidence generated by this northward-shifted, stronger ITCZ would lead to drying of the southern part of the Amazon basin.

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 because of 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, which are sometimes referred to as the expansion of the Hadley Cell (Held and Soden 2006; Meehl et al. 2007) (Figure 11). There

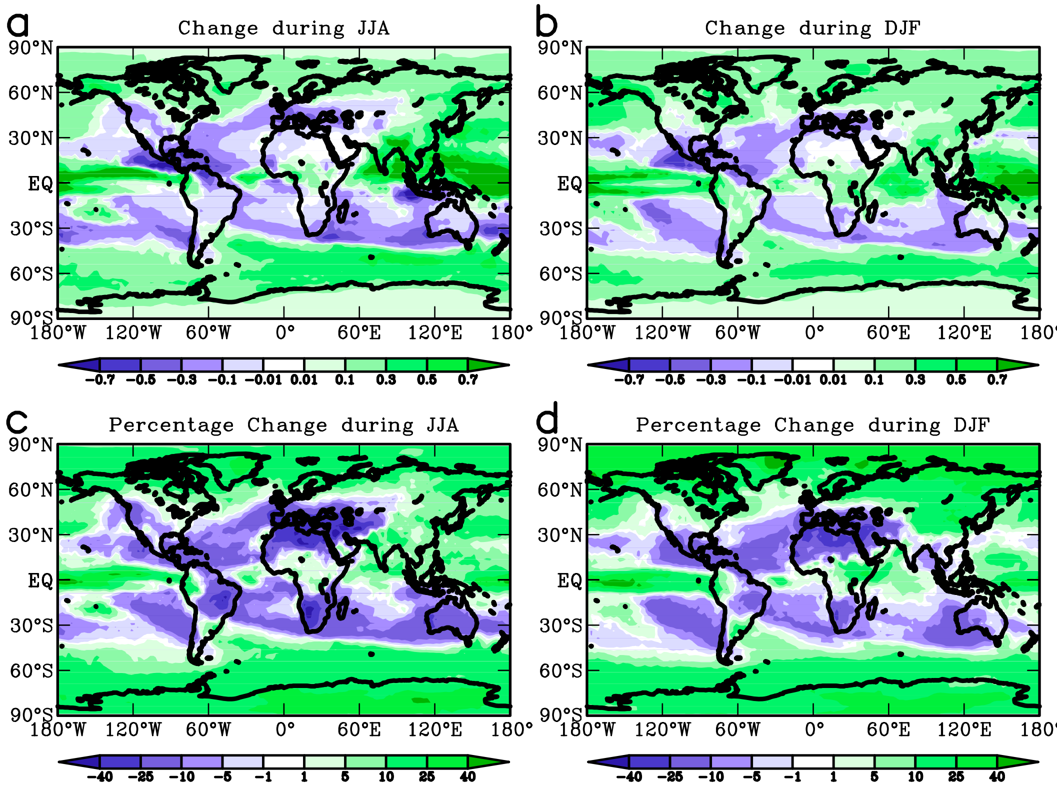

Figure 11. IPCC model median change in precipitation (mm day^{-1}) from the twentieth to twenty-first century for the northern summer (JJA) and winter (December–February (DJF)) seasons: (a) net change (mm day^{-1}) in JJA; (b) net change (mm day^{-1}) in DJF; (c) percentage change in JJA; and (d) percentage change in DJF. Note (i) the expansion of the subtropical dry zones, which coincides with reduced Amazonian rainfall during Northern Hemisphere summer; and (ii) the general strengthening of the ITCZ, which increases Amazonian rainfall during the Northern Hemisphere winter.

may be many factors that contribute to this change, but it is mostly a consequence of increased atmospheric humidity under warming. Following the simple Clausius–Clapeyron relation, an increase in humidity leads to more moisture convergence and thus more rainfall in the convergence zone; conversely, more moisture divergence [$\nabla \cdot (q\mathbf{v})$, where **v** is vector wind and the nabla sign is the del operator, which increases as air humidity q increases exponentially with temperature] thus leads to less rainfall in the divergence/subsidence region (Held and Soden 2006; Neelin et al. 2006; Seager et al. 2007). This is a change in which “the rich get richer and the poor get poorer.”

The question then becomes whether the region in question is part of the ITCZ convection band with upward motion that generates more rainfall or a part of the subtropical atmospheric subsidence zone, where rainfall is suppressed. Climatologically, during the dry season, the southern Amazon basin and central Brazil lie at the

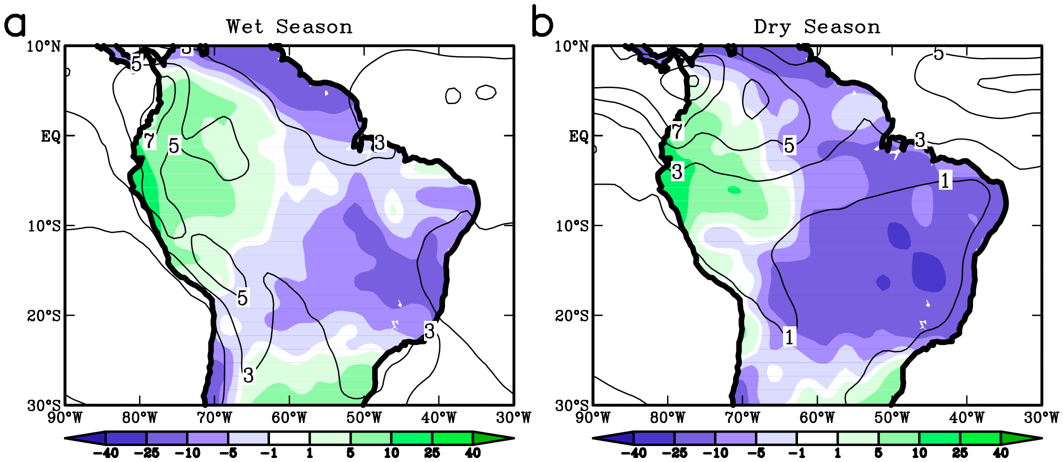

Figure 12. A graphic displaying the twentieth century rainfall (mm day^{-1}) in contours, with percentage change in SAB (a) wet and (b) dry season precipitation from the twentieth century to the twenty-first century overlain with shading. (a) Wet season change: the region where contours are in close 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.

western edge of a subtropical high pressure zone between the equatorial Amazonian convection center and the South Atlantic convergence zone (SACZ) (Figures 12, 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} (Figure 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 SAB is within the ITCZ; thus, we expect more wet season rainfall under climate change. This seasonal dynamical mechanism is illustrated in Figure 13.

Because the Atlantic SST gradient change persists year-round, it would also reduce rainfall in the wet season SAB. In contrast, the wetter ITCZ/drier subtropics mechanism discussed above would lead to a wetter wet season and a drier dry season. This cancellation may explain the relatively small change in precipitation during the wet season in the SAB (Figure 2b). Because the IPCC models project moderately increased rainfall during the wet season (Figure 2b; although with large scatter shown in Figure 7), one may infer that the wetter ITCZ mechanism may have 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 (Figure 13). This schematic diagram is consistent with some

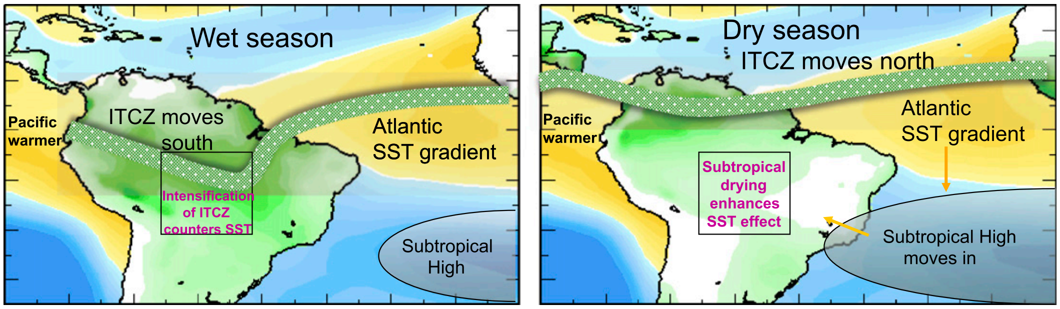

Figure 13. A schematic diagram showing the two mechanisms under climate change (general subtropical drying/stronger Atlantic SST gradient and eastern Pacific warming) that may work in concert to produce a robustly drier dry season in the southern Amazon basin and central Brazil (boxed area). These mechanisms act in opposite directions in the Amazonian wet season, leading to relatively small precipitation changes in the wet season. Background colors indicate climatological rainfall on land (green), the subtropical high pressure system (gray), and median IPCC model-projected late-twenty-first-century SST with tropical mean removed (light brown and blue).

previous studies. For example, enhanced (depleted) moisture flux toward the Amazon River mouth (southern Amazonia) is simulated by a regional climate model (Cook and Vizy 2008) and the similar result that atmospheric moisture convergence increases (decreases) along the ITCZ (subtropics in both the Southern and Northern Hemispheres) is simulated by the Coupled Model Intercomparison Project, phase 3 (CMIP3; Seager et al. 2007).

6. Discussion and conclusions

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 basin and to shed light on the important but controversial issue of possible Amazon rain forest dieback.

Our results suggest that an Amazon basinwide 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 24 IPCC models we analyzed and such a possibility cannot be excluded. Rather than drawing a general conclusion for the whole Amazon basin, we find contrasting behaviors for different parts of Amazonia. In particular, western Amazonia, the core of the rain forest, which is very wet even during the dry season, will have higher rainfall, which would largely counter potential adverse effects due to warming on soil moisture and vegetation.

However, southern Amazonia and central Brazil may suffer major ecosystem degradation because of climate change. There is strong agreement among the models 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 (Figure 13), including the following changes in the atmosphere and ocean in response to greenhouse warming:

1) the general subtropical drying under climate change and the seasonal movement of the ITCZ and associated subtropical subsidence and
2) a warmer subtropical North relative to the South Atlantic Ocean and, to lesser degree, a warmer, more El Niño–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 the following:

1) dry season rainfall change having a disproportionately large impact on soil moisture,
2) loss of soil moisture due to warming-enhanced evaporative demand, and
3) higher maintenance cost (autotrophic respiration) and possibly reduced photosynthesis as the temperature increases.

One factor that might work in the opposite direction is the CO_2 fertilization effect because higher CO_2 concentration may stimulate vegetation productivity and increase efficiency of water use. Indeed, model sensitivity experiments (Lapola et al. 2009) show a vegetation change similar to ours without the CO_2 fertilization effect but an increase in Amazonian vegetation when the effect is included. To measure the impact of CO_2 fertilization, an additional sensitivity experiment was performed in which the CO_2 fertilization effect was turned off. In our standard experiment with this effect, the median LAI over SAB decreases by 0.77, but the reduction in LAI is 0.89 without CO_2 fertilization. Thus, CO_2 fertilization partially mediates the decline in LAI across Amazonia, as expected. However, this difference is much smaller than in the previous study (Lapola et al. 2009), where CO_2 fertilization was able to largely cancel out the climate effects. This difference is likely due to the relatively weak CO_2 fertilization effect in VEGAS compared to some other models (Friedlingstein et al. 2006). The weaker CO_2 fertilization employed in VEGAS appears to be in line with recent research, especially for mature forests, although a consensus has not been reached (Caspersen et al. 2000; Field 2001; Hungate et al. 2003; Körner et al. 2005; Luo et al. 2004). This model dependence remains a key source of uncertainty, with major implications for future ecosystem response in many other regions as well (Mahowald 2007; Zeng and Yoon 2009). Another source of uncertainty comes from the high temperature tolerance of tropical plants. Recent studies found controversial results regarding how tropical plants respond to higher temperature (Doughty and Goulden 2008; Lloyd and Farquhar 2008; Rosolem et al. 2010). In VEGAS, warmer surface air temperature can affect soil moisture and induce vegetation water stress more directly. Further research of this issue is required to reduce uncertainty.

During the review process of this paper, we became aware of the work of Malhi et al. (Malhi et al. 2009), who focused on eastern Amazonia (EA) and found results similar to our analysis [i.e., reduced precipitation, soil moisture (Figure 2), and vegetation (Figure 9b)], thus drawing attention to potential vulnerability in the eastern Amazon basin. We focused here on the southern Amazon basin and central

Brazil because the region is climatologically drier and subject to a more widespread threat of deforestation.

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, even in the same region and sometimes in opposite directions. In the case of southern Amazonia, a general subtropical drying mechanism and an increased Atlantic SST gradient work together to produce a robust drier dry season, whereas, 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 linkage to lower Amazonia, which tends to be locked to Northern Hemisphere winter, and in the recently highlighted connection between the Atlantic SST gradient and southern Amazonia, as was seen during the 2005 drought (Marengo et al. 2008; Yoon and Zeng 2010; Zeng et al. 2008). Although most of the coupled climate models in CMIP3 have consensus in change of north–south gradient of SST in Atlantic and southern Amazon rainfall, it is cautiously noted here that the most of coupled models have difficulty in simulating proper SST gradient in zonal direction over the Atlantic sector (Richter and Xie 2008), which might have influence on overall simulation.

The decrease in dry season rainfall is relatively small in its absolute magnitude. The drying corresponds to a lengthening of the dry season by about 10 days, where the dry season is defined as rainfall below 1 mm day^{-1} (Figure 6a). Because the data are monthly, the result of interpolation is a 10-day lengthening, and the data thus have relatively large uncertainty. The strong response in vegetation suggests highly nonlinear processes at play. One nonlinear process is in terrestrial hydrology because a greater percentage of dry season precipitation is used by the ecosystem because a larger proportion of wet season precipitation than dry season precipitation goes into runoff. On the ecological side, the rain forest 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 2002–05 Amazon drought (Zeng et al. 2008), the 2005 drought in Amazonia (Phillips et al. 2009), and most dramatically by a multiyear precipitation-shielding experiment in the Amazon rain forest (Fisher et al. 2007; Nepstad et al. 2007) where 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 (Charney 1975; Da Silva et al. 2008; Dickinson and Henderson-Sellers 1988; Saad et al. 2010; Shukla et al. 1990; Zeng and Neelin 1999). Surface degradation leads to higher albedo, reduced evaporation, and other changes during the dry season, and southern Amazonia may see further rainfall reduction during its dry season when these processes are fully considered.

These climatic and ecological changes may have a dramatic effect on the landscape, biodiversity, carbon cycle, and economy of southern Amazonia 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.

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Appendix

The IPCC models are multimodel ensembles, run with radiative forcings estimated for the twentieth century and the SRES A1B scenario for the twenty-first century. The models included in this analysis are listed in Table A1. Details of the models can be found online (at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php).

The models are interpolated onto a common $2.5° \times 2.5°$ grid. The change in climatology noted in the late twenty-first century (2070–99 average) relative to a base period (1961–90 average) is averaged over the southern Amazonia box (shown in Figure 1a) and computed for all 24 models. Then, the median of the aforementioned change and that of the time series are obtained to represent the average model behavior. A fractional change (measured in percent) of the base-period climatology is computed for each individual model and the median of the models is obtained in the same manner. It is also noted here that some models do not provide all the variables, especially soil moisture and runoff used in Figure 8. We used the maximum number of the models possible.

The offline Vegetation–Global–Atmosphere–Soil (VEGAS) model was forced individually by the 24 model climates for variables such as precipitation and temperature from 1901 to 2099, and then the results are analyzed for their changes. We use the median for each variable of the 24 models for simplicity as well as 25th/75th percentile to assess uncertainty.

The terrestrial carbon model VEGAS (Zeng 2003; Zeng et al. 2005a; Zeng et al. 2004) simulates the dynamics of vegetation growth and competition among different plant functional types (PFTs). It includes four PFTs: broadleaf tree, needleleaf tree, cold grass, and warm grass. The different photosynthetic pathways are distinguished for C_3 (the first three PFTs above) and C_4 (warm grass) plants.

Table A1. List of the 24 climate models used in our analysis. Details of the models can be online (at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php). Model names not expanded in the text include the following: Bjerknes Centre for Climate Research Bergen Climate Model version 2 (BCCR-BCM2.0); Centre National de Recherches Météorologiques Coupled Global Climate Model, version 3 (CNRM-CM3); GISS Atmosphere–Ocean Model (GISS-AOM); GISS Model E-H (GISS-EH); Instituto Nazionale di Geofisica e Vulcanologia (INGV) ECHAM4; Meteorological Institute of the University of Bonn, ECHO-G Model (MIUBECHOG); Meteorological Research Institute Coupled General Circulation Model, version 2 (MRI CGCM2); National Center for Atmospheric Research (NCAR) Community Climate System Model, version 2 (CCSM2); and NCAR Parallel Climate Model version 1 (PCM1).

Model name	Institution	Country
BCCR-BCM2.0	Beijing Climate Center	China
CCCMA CGCM3.1	Canadian Center for Climate Modeling and Analysis	Canada
CCCMA CGCM3.1-T63	Canadian Center for Climate Modeling and Analysis	Canada
CNRM-CM3	Meteo-France/Centre National de Recherches Meteorologiques	France
CSIRO MK3	Commonwealth Scientific and Industrial Research Organization	Australia
CSIRO MK3.5	Commonwealth Scientific and Industrial Research Organization	Australia
ECHAM5	Max Planck Institute	Germany
GFDL CM2.0	NOAA/GFDL	United States
GFDL CM2.1	NOAA/GFDL	United States
GISS-AOM	NASA Goddard Institute for Space Studies	United States
GISS-EH	NASA Goddard Institute for Space Studies	United States
GISS-ER	NASA Goddard Institute for Space Studies	United States
HadCM3	UKMO/Hadley Centre	United Kingdom
HadGEM1	UKMO/Hadley Centre	United Kingdom
IAP FGOALS-g1.0	IAP Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG)	China
INGV ECHAM4	Instituto Nazionale di Geofisica e Vulcanologia	Italy
INM-CM3.0	Institute for Numerical Mathematics	Russia
IPSL CM4	Institut Pierre Simon Laplace	France
MIROC3.2(medres)	Center for Climate System Research, University of Tokyo	Japan
MIROC3.2(hires)	Center for Climate System Research, University of Tokyo	Japan
MIUBECHOG	Meteorological Institute of the University Bohn, Meteorological Research Institute of the Korea Meteorological Administration (KMA), and Model and Data Group	Germany/South Korea
MRI CGCM2	Meteorological Research Institute	Japan
NCAR CCSM3	National Center for Atmospheric Research	United States
NCAR PCM1	National Center for Atmospheric Research	United States

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 (Qian et al. 2008; Zeng et al. 2005b). The vegetation component is coupled to land 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 time scales in the tropics (Zeng et al. 2005a). The vegetation module is coupled to a two-layer land surface model (SLand; Neelin and Zeng 2000) that is driven by precipitation, temperature, wind, and other atmospheric variables. The land model provides soil moisture and soil temperature to VEGAS, which in turn modifies evapotranspiration through photosynthesis–stomata interaction. The land–vegetation model is run at a daily time step.

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