Rainfall and its seasonality over the Amazon in the 21st century as assessed by the coupled models for the IPCC AR4

Wenhong Li, Rong Fu, and Robert E. Dickinson
Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA

Received 10 June 2005; revised 7 November 2005; accepted 17 November 2005; published 28 January 2006.

The global climate models for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) predict very different changes of rainfall over the Amazon under the SRES A1B scenario for global climate change. Five of the eleven models predict an increase of annual rainfall, three models predict a decrease of rainfall, and the other three models predict no significant changes in the Amazon rainfall. We have further examined two models. The UKMO-HadCM3 model predicts an El Niño-like sea surface temperature (SST) change and warming in the northern tropical Atlantic which appear to enhance atmospheric subsidence and consequently reduce clouds over the Amazon. The resultant increase of surface solar absorption causes a stronger surface sensible heat flux and thus reduces relative humidity of the surface air. These changes decrease the rate and length of wet season rainfall and surface latent heat flux. This decreased wet season rainfall leads to drier soil during the subsequent dry season, which in turn can delay the transition from the dry to wet season. GISS-ER predicts a weaker SST warming in the western Pacific and the southern tropical Atlantic which increases moisture transport and hence rainfall in the Amazon. In the southern Amazon and Nordeste where the strongest rainfall increase occurs, the resultant higher soil moisture supports a higher surface latent heat flux during the dry and transition season and leads to an earlier wet season onset.


1. Introduction

[2] Previous modeling studies have found that changes in external oceanic and internal land surface feedback resulting from increasing atmospheric CO₂ could lead to a decrease of rainfall and persistent drought over the Amazon causing “dieback” of the rainforest and further increase in the atmospheric CO₂ in the 21st century [Cox et al., 2004]. On the other hand, Costa and Foley [2004] found that the overall effect of doubled CO₂ concentrations is an increase in basin-averaged precipitation of 0.28 mm day⁻¹ in their analysis of the combined effects of deforestation and increased CO₂ over the Amazon in simulations with the “GENESIS-IBIS” climate model. Therefore, it is still an open question as to whether a drier or wetter future climate over the Amazon should be predicted by climate models.

[3] The dry season length largely determines the vegetation types at a given location in the tropics [Sombroek, 2001; Sternberg, 2001]. It is strongly influenced by both the sea surface temperature (SST) over the adjacent tropical oceans [Liebmann and Marengo, 2001; Fu et al., 2001] and the local soil moisture/vegetation [Jipp et al., 1998; Nepstad et al., 2002; Fu and Li, 2004]. However, the mechanisms by which climate change could influence its length have not been thoroughly examined.

[4] The Coupled Model Intercomparison Project (CMIP) provides simulation results from various coupled ocean-atmospheric general circulation models (GCMs). These models simulate the climate in the 21st century for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) according to the changes in climate forcing, including increase of atmospheric carbon dioxide. They use the “Special Report on Emission Scenarios” (SRES) which explored possible pathways of future greenhouse gas emissions. The CMIP archives allow us to examine the rainfall climatology for the current climate and its change for doubling atmospheric CO₂ across different climate models.

[5] If the length of the dry season were to increase, the reduced rainfall could change vegetation from forest to savanna. Such a “dieback” of the rainforest would not only influence the ecology and socio-economics of the Amazon but also release terrestrial carbon to the atmosphere and further amplify the global warming [Cox et al., 2000]. On the other hand, if the length of the dry season were to shorten, rainfall would increase, the remaining rainforest should be stable, and secondary forest could grow more rapidly. The Amazon forest could then be a sink instead of a source of atmospheric CO₂ [Tian et al., 1998]. Thus, future global atmospheric CO₂ is particularly sensitive to the
change of rainfall and the length of the dry season over the Amazon.

[6] We examine all the available models for the IPCC AR4 for the changes of Amazon rainfall during the 21st century. The seasonal cycle of the precipitation and related variables in the 20th century simulations are compared to the observational data to determine reasonableness of the processes critical for the length of the dry season. We perform more detailed analyses of two models that best simulate rainfall seasonality for the 20th century but predict opposite changes of rainfall in the 21st century. Finally, we discuss the uncertainties in the predicted rainfall changes and their potential impacts on the regional hydrological cycle, ecosystem, and land use.

2. Models, Emission Scenario, and Experiments

[7] This study uses standard output from Coupled Ocean-Atmosphere GCMs for the IPCC AR4, rain gauge data [Liebmann and Marengo, 2001; Marengo et al., 2001], and the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CDC) Merged Analysis of Precipitation (CMAP) data. The rain gauges are located within the Brazilian Amazon Basin, and the data were originally collected by the National Water and Electric Energy Agency of Brazil (ANEEL). CMAP data are available from the NOAA CDC website and were estimated by combining satellite observations of clouds and rain gauge measurements [Xie and Arkin, 1996, 1997].

[8] We have examined the rainfall variations in the 21st century simulations under the emission scenario A1B (SRES A1B) for all available models for the IPCC AR4. The A1B scenario describes a future world of very rapid economic growth and global population that peaks in mid-century and declines thereafter and describes the rapid introduction of new and more efficient technologies [Nakicenovic et al., 2000]. Fossil fuels and other energy sources are balanced in SRES A1B. Figure 1 shows the concentration of SRES A1B CO2. The initial conditions in SRES A1B are from a simulation of climate at the end of the 20th century (20C3M) that in turn was initialized from a point early enough in the pre-industry control run. They represent the current climate in each model with a temporal change of global mean CO2 mixing ratios from 350 to 370ppm from 1990 to 2000. The CO2 concentration doubles to 720ppm in 2100 at the 21st century simulations (Figure 1), after which it is fixed.

[9] Simulations from the 11 models for the IPCC AR4 are available to study the precipitation change due to CO2 increase over the Amazon in both the 20th and the 21st century runs. Table 1 lists the 11 models, their particular ensemble members used in the study, the time periods of the data sets span, and the models' resolutions.

[10] We compare the 21st century runs with those for the 20th century to investigate how precipitation changed and therefore how the length of the dry season was modified. The peak of rainy season varies from July in the northern Amazon to January in the southern Amazon [Satyamurty et al., 1998]; we examine averaged rainfall over the southern Amazon region (5°–15°S, 45°–75°W) where all points have similar seasonal cycles, with wet season onset in austral spring, peak in summer, and end in austral fall [Kousky, 1988; Marengo et al., 2001; Li and Fu, 2004]. For the purpose of assessing impacts, we define the dry season as the period during which monthly rainfall is less than 100 mm. This criterion represents the minimum rainfall needed for maintaining an evergreen rain forest [France, 1986; Sternberg, 2001] and is also commonly used for ecological-economic zoning [Sombroek, 2001].

[11] In order to evaluate how well the models represent the current climate, the seasonal cycles of the precipitation over the Amazon region are compared to those derived from gauge data and CMAP data while focusing on the GFDL-CM2.1, GISS-ER, NCAR-CCSM3, and UKMO-HadCM3 models. Their outputs provide land surface as well as large-scale atmospheric variables that allow us to evaluate the key processes controlling the seasonality of rainfall in the current climate. We use in situ measurements of surface latent and sensible heat fluxes and absorbed surface solar radiation provided by the Large-scale Biosphere Atmosphere (LBA) field experiments for the Biological Reserve of Jaru (hereafter referred to as Jaru) at 10°05'S, 61°55'W. The measurements were carried out from February 1999 to September 2002 [von Randow et al., 2004]. Soil moisture data are digitized from Figure 5 in von Randow et al. [2004]. The total large-scale moisture convergence is calculated from the net zonal and meridional moisture transport \(\Delta(uq)\) and \(\Delta(vq)\), respectively, to the Southern Amazon region. Zonal moisture fluxes are computed at each time step of instantaneous model output and then integrated from 1000 hPa to 100 hPa and from 5°S to 15°S along 75°W \(\{uq\}_{75°W,5°S–15°S}\) and 45°W \(\{uq\}_{45°W,5°S–15°S}\), respectively. The net zonal moisture convergence \(\Delta(uq)\) is calculated by the difference between these terms. A positive value of \(\Delta(uq)\) represents a net zonal moisture convergence to the region. Similarly, \(\{vq\}_{5°S,45°–75°W}\) and \(\{vq\}_{15°S,45°–75°W}\) are meridional moisture fluxes integrated from 1000 hPa to 100 hPa and from 45°W to 75°W along 5°S and 15°S, respectively. The net meridional moisture transport \(\Delta(vq)\) is computed from the difference between these two meridional moisture transport terms. The total moisture convergence to the Southern Amazon region, i.e., the sum of \(\Delta(uq)\) and \(\Delta(vq)\), is then converted into precipitable water per day per square meter, in order to compare with the rain rate.
Table 1. IPCC Climate Models Used in the Study

<table>
<thead>
<tr>
<th>Models</th>
<th>Institutes (Country)</th>
<th>Output Periods (Ensemble Member Used)</th>
<th>Resolutions</th>
<th>Web Site and References</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNRM-CM3</td>
<td>Météo-France/Centre National de Recherches Météorologiques (France)</td>
<td>20C3M: (run 1) 01/1860–12/1999 A1B: (run 1) 01/2000–12/2300</td>
<td>Atm: T42 Ocn: 2° lat, varying lon. (0.5° at equ. to 2° in polar regions)</td>
<td><a href="http://www-pcmdi.llnl.gov/ipcc/model_documentation/CNRM-CM3.doc">http://www-pcmdi.llnl.gov/ipcc/model_documentation/CNRM-CM3.doc</a></td>
</tr>
<tr>
<td>ECHAM5/ MPI-OM</td>
<td>Max Planck Institute for Meteorology (Germany)</td>
<td>20C3M: (run 3) 01/1860–12/2101 A1B: (run 1) 01/2001–12/2200</td>
<td>Atm: T63 L31 Ocn: 1.5° conformal mapping grid with grid poles over Greenland &amp; Antarctica</td>
<td><a href="http://www-pcmdi.llnl.gov/ipcc/model_documentation/ECHAM5_MPI-OM.doc">http://www-pcmdi.llnl.gov/ipcc/model_documentation/ECHAM5_MPI-OM.doc</a></td>
</tr>
<tr>
<td>GFDL-CM2.1</td>
<td>US Dept. of Commerce/ NOAA/Geophysical Fluid Dynamics Laboratory (USA)</td>
<td>20C3M: (run 3) 01/1861–12/2000 A1B: (run 1) 12/2000–12/2300</td>
<td>Atm:2.0° lat. × 2.5° lon. Ocn: 1° lat. × 1° lon. enhanced tropical resolution (1/3 on the equator)</td>
<td><a href="http://www-pcmdi.llnl.gov/ipcc/model_documentation/GFDL-cm2.doc">http://www-pcmdi.llnl.gov/ipcc/model_documentation/GFDL-cm2.doc</a></td>
</tr>
<tr>
<td>MRI-CGCM2.3.2</td>
<td>Meteorological Research Institute (Japan)</td>
<td>20C3M: (run 5) 01/1851–12/2000 A1B: (run 5) 01/2001–12/2300</td>
<td>Atm: T42 Ocn: 2.5° lon., 0.5° lat. (4S–4N) ~2° lat. poleward 125° &amp; 12N</td>
<td><a href="http://www-pcmdi.llnl.gov/ipcc/model_documentation/MRI-CGCM2.3.2.doc">http://www-pcmdi.llnl.gov/ipcc/model_documentation/MRI-CGCM2.3.2.doc</a></td>
</tr>
<tr>
<td>NCAR-CCSM3</td>
<td>National Center for Atmospheric Research (USA)</td>
<td>20C3M: (run 5) 01/1870–12/1999 A1B: (run 5) 01/2000–12/2199</td>
<td>Atm: T85L26 Ocn: g × 1v3</td>
<td><a href="http://www.cccsm.ucar.edu/models/">http://www.cccsm.ucar.edu/models/</a></td>
</tr>
</tbody>
</table>

[12] We further focus on two models, GISS-ER and UKMO-HadCM3, which realistically represent the seasonal changes of the precipitation and the land surface fluxes over the Amazon region in their 20th century simulations. For the 20th century, we only consider the period from January 1970 to December 1999; for the 21st century run, we study the precipitation changes on a monthly time scale starting from January 2101 to December 2130. This is the first 30-year period after the atmospheric CO₂ has stabilized at 720 ppm. A 30-year period is chosen to minimize the possible phase difference in decadal climate changes among different models. In the following discussion, unless it is specified explicitly, all changes such as precipitation, land surface conditions, sea surface temperature, and other large-scale conditions refer to the differences between the period of 2101–2130 and the period of 1970–1999. We also briefly discuss the potential climate impacts on ecosystem and land use over the Amazon based on predicted rainfall changes.

3. Results

3.1. Changes of Precipitation in the 21st Century Compared to the 20th Century

[11] Figure 2 shows the annual mean rainfall and the variability over the southern Amazon region of 11 models for the last 50 years in the 20th (1950–1999) and the 21st (2050–2099) centuries. Such climatological annual mean rainfall in the 20th century are also compared to those observed by rain gauges, CMAP, and 15-year European Center for Medium-Range Weather Forecasts Re-Analysis (ERA15, 1979–1993) in Figure 2. Compared to gauge data,
CMAP (ERA15) underestimated (overestimated) the annual mean precipitation by about 1.1 (1.0) mm day$^{-1}$. The climatological annual mean rainfall in the 20th century varies from 2.7 mm day$^{-1}$ to 5 mm day$^{-1}$ among the 11 models compared to 5.3 mm day$^{-1}$ suggested by gauges for the same period and 4.2 mm day$^{-1}$ by CMAP data for the period of 1979 to 1999 (Figure 2). Thus, most models underestimate the rain rate, some more than others. The amplitude of interannual to decadal variations of rainfall, as indicated by the standard deviations of the annual rainfall in all the models are weaker than that suggested by rain gauges (0.7 mm day$^{-1}$, or 257 mm annually) but comparable to that of CMAP (0.3 mm day$^{-1}$, or 110 mm annually). The simulated climate variability is the strongest in the GFDL-CM2.1 and UKMO-HadCM3 models (about 0.5 mm day$^{-1}$).

[14] In the 21st century, the annual mean precipitation increases in five models, i.e. the CNRM-CM3, GISS-EH, GISS-ER, IPSL-CM4, and NCAR-CCSM3 models, but it decreases in the GFDL-CM2.1, MIROC3.2 (medium resolution) and UKMO-HadCM3 models, and it remains more or less unchanged in the remaining three models, i.e., the INM-CM3.0, ECHAM5/MPI-OM, and MRI-CGCM2.3.2 models. The variability of annual rainfall increases in the UKMO-HadCM3 and ECHAM5/MPI-OM models, and it remains essentially unchanged in the rest.

[15] We choose the GFDL-CM2.1, GISS-ER, NCAR-CCSM3, and UKMO-HadCM3 models to analyze in detail their correspondence to current climate on the basis of the availability of data for fields of precipitation, land surface, and large-scale atmosphere in their 20th century run. Two models, GFDL-CM2.1 and UKMO-HadCM3, predict decreases of precipitation, whereas the other two, GISS-ER and NCAR-CCSM3, predict increases (Figure 2). Figure 3 shows the climatological precipitation in the 20th and 21st century and their comparisons with the gauge, CMAP, and ERA15 over the Amazon region for the four models. Compared to gauges, CMAP and ERA15 showed similar seasonal cycles of the precipitation over the Amazon, although ERA15 overestimated the rain rate from April to October by as much as 2 mm day$^{-1}$ in the dry season, and CMAP underestimated the rain rate with maximum deficit in the wet season. The difference between the CMAP and gauge data is probably due to an underestimation of warm rain over the Amazon by satellites.

[16] The rainfall climatology in the 20th century experiments of the UKMO-HadCM3 is within the observational uncertainty during the transition from the dry to the wet seasons. Its most significant disagreement is in the dry season (Figure 3a). The modeled rainfall is nearly zero from June to August, and also underestimated by about 1 to 2 mm day$^{-1}$ (30–60 mm per month or 25% ~ 30%) in May and June compared to that of the gauges and CMAP. The GFDL-CM2.1 model also underestimates precipitation by 2 to 3 mm day$^{-1}$ during the dry season and the transition to the wet season (September–November), leading to a seven-month long dry season in the both 20th and 21st century runs (Figure 3d). Such a long dry season exceeds the limit (of about six months) for sustaining a rainforest [Sombroek, 1966; Prance, 1986].

[17] The GISS-ER climatological rain rates in the dry and the transitional seasons (July–October) agree well with those from rain gauges and CMAP, but are underestimated by about 2 to 3 mm day$^{-1}$ compared to gauge and about 1 mm day$^{-1}$ compared to the CMAP data during the peak wet season (Figure 3b). NCAR-CCSM3 presents a similar result as GISS-ER in its 20th century run: the model’s rainfall climatology reasonably agrees with the observational data from October to December but is about 1 mm day$^{-1}$ lower than the observations in the dry season especially from June to September. Its precipitation agrees with CMAP from January to April but is about 2 mm day$^{-1}$ lower than gauge data (Figure 3c). Overall, these three models adequately simulate the precipitation seasonality and the length of the dry season over the Amazon (Figures 3a, 3b, and 3c).

[18] Figure 3 also shows a decrease of precipitation in the UKMO-HadCM3 and GFDL-CM2.1 models in the transition from the dry to the wet season as atmospheric CO2 increases in the 21st century. In the UKMO-HadCM3 model, the transition from dry to wet season, as indicated by increase of rainfall in early austral spring, begins about one month later than that in the 20th century and so prolongs the dry season. The GISS-ER and NCAR-CCSM3 models, however, predict a trend of increased rainfall. In the GISS-ER model, precipitation increases starting from September with greatest values in November and December.
NCAR-CCSM3 also predicts more precipitation throughout the year except for April. The increase of the rainfall predicted by GISS-ER and NCAR-CCSM3 models in their 21st century experiments shortens the dry season.

The length of dry seasons, defined by the number of months with rainfall less than 100 mm, is evaluated in the UKMO-HadCM3 and GISS-ER 20th century simulations in Figure 4 by comparing to CMAP data. The CMAP data (Figure 4a) shows that the length of dry seasons is about one to three months in the western equatorial Amazon, and that it increases eastward and southeastward to five to six months in the eastern equatorial and southern Amazon. In most of the eastern Amazon and Nordeste regions, the dry season becomes eight to nine months. The short dry season in the western Amazon is a result of topographic moisture convergence forced by the east slope of the Andes of easterly trade winds from the Atlantic [Kleeman, 1989]. The long dry season in the most eastern Amazon is mainly due to subsidence connected to the Atlantic Inter-tropical Convergence Zone (ITCZ) [Fu et al., 2001]. The observed spatial pattern of dry season length is largely captured by the UKMO-HadCM3 20th century simulation (Figure 4b), except that it overestimates its length by one month. The length of the dry season for the GISS-ER 20th century (Figure 4c) generally increases with latitude in the Southern Hemisphere. Its lack of an east-west gradient of dry season length is probably the result of a lack of resolution (cf. Table 1) which unrealistically flattens the Andes, and the lower resolution could also weaken the Atlantic ITCZ.

Figure 5 shows changes in length of the dry season predicted by the UKMO-HadCM3 and GISS-ER models. UKMO-HadCM3 shows an increase of the dry season of about one to two months (Figure 5a) and a reduction of annual mean rainfall by over 1 mm day$^{-1}$ (Figure 6a). This decline in rainfall and lengthening of the dry season from its already excessive length in the 20th century (Figure 5a) would likely cause a transition from rain forest to savanna/scrub [Sombroek, 2001]. GISS-ER, on the other hand, predicts about a one-month decrease of the dry season over the southern Amazon and the Nordeste regions (Figure 5b) compared to its 20th century climate.

The spatial distributions of precipitation change in the 21st century for annual mean and December (when the maximum differences of the rain rate for the two models occur) are shown in Figure 6. UKMO-HadCM3 predicts a decrease of precipitation that is largest in the central and eastern tropical Amazon (Figure 6a). Its December rainfall decreases over all the area north of 20$^\circ$S (Figure 6c) and averages about 3–4 mm day$^{-1}$. In contrast, GISS-ER shows an increase of precipitation mainly in the tropical Amazon and Nordeste area (Figure 6b). Its December precipitation increases over the entire Amazon with a stronger and more southward Atlantic ITCZ (Figure 6d). Figure 6 shows that the precipitation changes of the two models are opposite over the entire basin with an especially large contrast over
3.2. Possible Processes Causing the Precipitation Change in the 21st Century

3.2.1. How Do Changes of the Pacific and Atlantic SSTs Influence the Amazon Rainfall?

Precipitation and the length of the dry season over the Amazon are influenced by the SSTs over the Pacific and Atlantic oceans. Previous studies have documented that, during El Niño (La Niña) years precipitation tends to decrease (increase) over the northeastern Amazon [Hastenrath and Heller, 1977; Aceituno, 1988; Chu, 1983; Marengo, 1992]. The tropical Atlantic interhemispheric SST anomalies also directly impact precipitation in the Amazon and Nordeste area [Moura and Shukla, 1981; Mechozo et al., 1990; Marengo, 1992; Hastenrath and Greischar, 1993; Uvo et al., 1998; Folland et al., 2001; Fu et al., 2001]. If the North (South) tropical Atlantic is anomalously warm, a positive (negative) SST gradient between tropical North and South Atlantic shifts the Atlantic ITCZ northward in the direction of the gradient and so suppresses (favors) rainfall over the Amazon and Nordeste, especially during summer and fall [Nobre and Shukla, 1996; Ronchail et al., 2002].

How do SST changes over the Pacific and Atlantic Oceans influence the precipitation and the length of the dry season in the 21st century? Figure 7 shows the SST changes for the two models for the December–February season when El Niño peaks. The UKMO-HadCM3 model

---

**Figure 4.** Mean length of the dry season as (a) observed by CMAP (1979–1999); (b) simulated by UKMO-HadCM3 (1970–1999); and (c) simulated by GISS-ER (1970–1999). The southern Amazon domain is indicated by the dashed box in each panel. Contour interval is one month. The dry season length locally statistically significant at 95% confidence levels is plotted.

**Figure 5.** Changes in the dry season length for the period of 2101–2130 from that of 1970–1999 predicted by (a) UKMO-HadCM3; and (b) GISS-ER. The southern Amazon domain is indicated by the dashed box in each panel. Contour interval is one month. Solid (dashed) lines show the months of dry season increase (decrease) in Figures 5a and 5b, respectively. The southern Amazon domain is indicated by the dashed box in each panel. The changes of the dry season length that are locally statistically significant at 95% confidence levels are plotted.
suggests a spatial El-Niño like SST change (Figure 7a). Its strongest warming, 3K, is found over the eastern Pacific. This El Niño-like SST change agrees with the results of Cox et al. [2004], who used the same HadCM3 model but included a dynamic global vegetation model under the IS92a “business as usual” emission scenario. In the IS92a scenario, the CO₂ concentration is about 980 ppm in 2100 or about 280 ppm higher than in SRES A1B. Corresponding to the El Niño-like SST change, the Walker circulation shifts eastward placing its downward branch over the Amazon (Figure 8a) and so reduces precipitation as shown in Figure 3a.

[24] The GISS-ER model shows a weaker warming over the Pacific in the 21st century compared to that simulated by UKMO-HadCM3. In addition, the warming is more apparent over the western Pacific (2K) than over the eastern Pacific (Figure 7b). This east-west gradient in the Pacific SST change would re-enforce the western Pacific centered Walker circulation (Figure 8b). The change of SST gradient suggested in the GISS-ER model seems to agree with the observed SST-tendency found by Cane [2005, Figure 5] which is in part contributed by the increase of greenhouse gases in the late 20th century.

[25] The two models show SST changes over the tropical Atlantic in the 21st century that would result in opposite changes of the inter-hemisphere gradient during the Amazon wet season (December–February). UKMO-HadCM3 predicts warmer SSTs in the northern tropical Atlantic, but SSTs in the southern tropical Atlantic remain similar. Such a change would push the Atlantic ITCZ further into the northern tropical Atlantic, thus reducing rainfall in the Amazon [Moura and Shukla, 1981; Fu et al., 2001].

[26] The GISS-ER model predicts warming (cooling) in the southern (northern) tropical Atlantic. Such a decrease of the North Atlantic SST relative to the South Atlantic should contribute to the increase of rainfall over the Nordeste and eastern Amazon by enhancing oceanic moisture advection to these regions [Marengo, 1992; Czaja et al., 2002].

[27] The tropical Atlantic Ocean influences rainfall over the Amazon primarily through altering the large-scale transport of moisture to the region [Rao et al., 1996]. We have calculated the total moisture convergence to the Southern Amazon region integrated from 1000 hPa to 100 hPa. Figure 9 shows the annual cycle of the large-scale moisture convergence for the 20th and 21st century simulations. We also plot the large-scale moisture transport using ERA15. The moisture divergence of ERA15 in the dry season could be small by 2 mm day⁻¹ [Li and Fu, 2004] consistent with its overestimate of precipitation (Figure 3) and evapotranspiration (ET) of 3 mm day⁻¹ [Shuttleworth, 1988]. On the other hand, the UKMO-HadCM3 model that has 1 mm day⁻¹ less precipitation than observed apparently
has an overestimate of divergence by a comparable amount. This excess divergence, if under external dynamic control, would make the dry season drier and longer than that observed, e.g., the month delay in convergence during austral spring. UKMO-HadCM3 apparently somewhat overestimates the rate of increase of moisture transport from September to December and wet season rainfall to compensate for the excessive loss of moisture during the dry season. Its moisture convergence ends about a month earlier in austral fall than that of ERA15. In the 21st century simulation, its net moisture transport to the Amazon has no significant changes throughout the year except a decrease in December. Both the El Niño-like SST anomaly over the Pacific and the positive SST gradient over the tropical Atlantic Ocean (Figure 7a) can explain the weakening of the moisture transport to the Amazon in December [Moura and Shukla, 1981; Marengo, 1992].

The moisture transport simulated in GISS-ER agrees well with ERA15 from August to December in both trend and quantities, although the model underestimates the moisture convergence from February to June. In the 21st century simulation, moisture transport increases during the wet season but decreases during the dry season (e.g., in August). The transition from the net divergence to convergence during the transition season (August to October) is earlier and so also the wet season onset compared to that in the 20th century. The difference in the large-scale moisture transport response to the climate changes from increase of CO2 during the wet season (boreal winter) appears to be consistent with the expected influences of the SST changes.

In short, external forcing such as SST changes over the tropical Pacific and Atlantic are opposite for the two models. UKMO-HadCM3 shows a strong El Niño-like climate change, rainfall, and a warmer northern tropical Atlantic that together weaken the moisture transport to the Amazon, consequently decreasing rainfall in the central Amazon and the Nordeste areas. GISS-ER, on the other hand, with a warmer western Pacific and southern tropical Atlantic SST change, predicts a more southward Atlantic

Figure 7. Changes in SST distribution for the December–February season during the period of 2101–2130 from that of 1970–1999 simulated by (a) UKMO-HadCM3; and (b) GISS-ER. The differences of SST that exceed (less) 2 (–2) K in magnitude are shaded. Contour interval is 1 K.

Figure 8. Same as in Figure 7, but for the changes of velocity potential distribution at 200 hPa in December simulated by (a) UKMO-HadCM3; and (b) GISS-ER. The differences that exceed (less) 2 (–2) × 10^6 m² s⁻¹ are shaded. Contour interval is 1 × 10^6 m² s⁻¹. The southern Amazon domain is indicated by the dashed box in each panel.
3.2.2. How Do Internal Land Surface and Atmospheric Conditions Influence the Rainfall Change?

Land surface fluxes initiate the transition from the dry to the wet season and provide at least 50% of the water vapor for the rainfall over the Amazon \cite{Salati et al., 1979; Li and Fu, 2004}. The sensible and latent heat fluxes simulated by the UKMO-HadCM3 and GISS-ER models agree more closely with the observations than those from most of the other coupled GCMs for the IPCC AR4 (not shown). We first analyze the surface solar flux because it dominates the changes of surface sensible and latent heat fluxes in the Amazon \cite{Shuttleworth, 1988; Rocha et al., 2004}. Figure 10 examines the net solar radiation for the two models. We have plotted for comparison the in situ observed fluxes at the LBA site located at the center of the southern Amazon domain. The LBA observations represent point-wise measurements and thus are not directly comparable to the simulated area averaged surface fluxes over the southern Amazon domain.

In the 20th century, UKMO-HadCM3 simulates a seasonal cycle of the net solar radiation that is qualitatively similar to the observations, but which may significantly overestimate surface solar flux during the dry and transition seasons (July to November, Figure 10a). Such a possible overestimate of the dry season surface solar flux is also implied by its underestimation of rainfall (Figure 3a) and presumably cloudiness. The GISS-ER model, on the other hand, may overestimate the surface solar flux during the transition and wet seasons (September to May). The underestimation of rainfall by the GISS-ER model during the wet season (Figure 3b) also suggests a possible underestimation of cloudiness consistent with the high biases in surface solar flux during the transition to and from wet seasons. These high biases in surface solar flux during wet and transition seasons.

Figure 9. Annual cycles of the area averaged total moisture convergence and their error bars based on student-t test for (a) UKMO-HadCM3, and (b) GISS-ER integrated from 1000 to 100hPa. Solid and dashed lines represent the climatologies for the period of 1970–1999 and the period of 2101–2130, respectively. Solid lines with open circles represent the moisture convergence derived from ERA15 for the period of 1979–1993. Units: mm day$^{-1}$.

Figure 10. Annual cycles of absorbed surface solar flux and their error bars based on student-t test for (a) UKMO-HadCM3, and (b) GISS-ER, respectively. The domain averaged surface solar flux climatology is represented by the solid curves for the period of 1970–1999 and by the dashed curves for the period of 2101–2130. The solid lines with open circles represent the absorbed surface solar flux observed at the LBA site. Units: W m$^{-2}$.
seasons will lead to high biases in surface sensible and latent heat fluxes.

[32] In the 21st century simulation, UKMO-HadCM3 predicts an increase of net solar radiation throughout the year, especially during the transition and wet seasons (Figure 10a). The largest increase in the net solar radiation occurs in December when the strongest decrease of rainfall occurs (Figure 3a) during the mature phase of the wet season [Zhou and Lau, 1998]. The changes of net solar radiation agree with the changes of cloud cover in the UKMO-HadCM3 model (not shown). For the GISS-ER model simulation, the net solar radiation (Figure 10b) and cloud cover (not shown) do not have significant changes between the two centuries except for August.

[33] The responses of sensible and latent heat fluxes to change of net radiation are largely determined by the soil moisture and vegetation type over the Amazon. Figure 11 shows the comparisons of sensible and latent heat fluxes for the UKMO-HadCM3 and GISS-ER models with the observations. The Bowen ratio varies from around 0.2 for the wet season to 0.4 for the dry season. In situ observations have shown that the Bowen ratio varies less than 10% at forest sites across different parts of the Amazon and for different seasons [Shuttleworth, 1988; Gash and Nobre, 1997; Rocha et al., 2004; von Randow et al., 2004]. Thus, the Bowen ratio suggested in Figure 11 by the LBA data can be used to represent a basin scale Bowen ratio for the Amazon forest.

[34] Both UKMO-HadCM3 and GISS-ER have peak sensible heat fluxes in the austral spring transition season as observed (Figures 11a and 11b). However, these peak values may be too strong in UKMO-HadCM3 (two to three times higher, Figure 11a). The too high surface solar flux combines with very low soil moisture during the late dry and transition season to give these results. The surface sensible heat flux in the GISS-ER model is also too high, especially during the wet and transition seasons, again in response to its high bias in surface solar radiation. The surface latent heat flux simulated by UKMO-HadCM3 in its 20th century simulation may be more reasonable than its sensible heat flux, although it is underestimated during the dry season as a result of its shortage in rainfall. The GISS-ER simulation may have excessive latent heat flux during the wet season (Figure 11d). However, its rainfall is still lower (Figure 3b) than observed probably because of an underestimation of the moisture convergence (Figure 9).

[35] Figure 11 shows that the latent heat flux in the UKMO-HadCM3 model decreases in the 21st century as expected from its decreased rainfall (Figure 3a). Its increase of surface solar flux (Figure 10a) is balanced by an increase of surface sensible flux (Figure 11a), presumably due to a lack of soil moisture. In the GISS-ER simulation, the surface latent heat flux increases mostly during the dry to early wet seasons (June to December), whereas rainfall increases mostly during the wet season (November to April, Figure 3b). The surface solar and sensible heat fluxes do not change significantly (Figures 10b and 11b). Thus, the increase of surface latent heat flux during June to September cannot be supplied by additional contemporaneous rainfall. The higher rainfall in the previous wet season in austral fall (April or May, see Figure 3b) presumably supplies the needed soil moisture.

Figure 11. Same as in Figure 10, but for the annual cycles of (a and b) surface sensible heat flux and (c and d) latent heat flux simulated by UKMO-HadCM3 (Figures 11a and 11c) and by GISS-ER (Figures 11b and 11d), respectively.
of the rainforest moisture in the deep soil, which can be tapped by roots moisture reported by surface latent heat flux shown in Figure 11. Observed soil these changes can be used to explain the changes of the total column soil moistures in both models to see if vegetation and soil drainage. Figure 12 examines changes strongly depend on their treatment of land surface/ support a relatively high latent heat flux in the models. Moisture in deep soil can be extracted by vegetation and soil composition, and porosity, its value at one site cannot be extrapolated to basin scale, especially not quantitatively. However, the general pattern of the seasonal change observed at this site shows the influence of precipitation, surface latent heat flux, and drainage on soil moisture. The influences of seasonal rainfall and root uptake by the forest have a stronger influence on soil moisture below 2 m than that of drainage at this site [von Randow et al., 2004]. Figure 12a shows that the seasonal pattern of soil moisture in the UKMO-HadCM3 is similar to that of the in situ observation, namely, a peak in late wet season (February to May) and a minimum during the transition from dry to wet season (September to October). Figure 12 shows that observed soil moisture decreases about 40% from its wet season value during the dry and transition seasons at the forest site, a decrease mostly from root uptake to support ET [von Randow et al., 2004]. UKMO-HadCM3 shows less than a 30% decrease of soil moisture during the dry to transition seasons, consistent with its low surface latent heat flux. Figure 12b shows a similar seasonal pattern for GISS-ER soil moisture. Its seasonal pattern for the 20th century agrees qualitatively with the observations with soil moisture decreasing by about 30% during the dry and transition seasons. Both models seem to qualitatively capture the response of the soil moisture to seasonal rainfall, transpiration, and water drainage.

[37] The soil moisture of the UKMO-HadCM3 decreases during the wet season and remains the same during the dry season in the 21st century simulation. Its pattern is consistent with the rainfall changes. Soil moisture of the GISS-ER 21st century simulation increases the most during late wet season (March to May), perhaps due to accumulation of its increase of rain through the wet season, and it remains higher from June to July, peaking in the late wet season. This extra soil moisture is available to support the increase of surface latent flux during the transition season in response to the increase of the surface solar flux. By August and September, the extra soil moisture is gradually depleted as shown in Figure 12b.

4. Discussion
4.1. What Are the Main Uncertainties and Potential Biases in the Model Predictions?
[38] Uncertainties in the predicted SST changes in the tropical Pacific and Atlantic, clouds, and land surface feedback in the Amazon are the key sources of the uncertainties in predicted changes of Amazon rainfall. The predictions of how SST would change differ substantially among the coupled GCMs for the IPCC AR4. Strong discrepancies in the predicted SST changes in the tropical Pacific have been reported previously and are considered to be an important source of uncertainty in predicting future climate by current GCMs. For example, Collins [2004] has shown that the trends of SSTs caused by a 1% increase per year in greenhouse gases vary from El Niño-like to La Niña-like patterns among a group of 20 CMIP models, including HadCM3 and GISS models. His results further suggest that the models that most realistically simulate ENSO cycles in current climate tend to predict small or no trend towards either El Niño-like or La Niña-like patterns [Collins, 2004, Figure 11], although there remains a small probability for a change to El Niño-like pattern. A change to a La Niña-like pattern is observed at this site [von Randow et al., 2004].
Atlantic and consequently opposite rainfall changes over the eastern Amazon [Moura and Shukla, 1981; Fu et al., 2001].

[40] Underestimation of clouds over the Amazon leads up to a 20% overestimation of surface solar flux in the dry season in UKMO-HadCM3. This causes a strong overestimation of surface sensible flux. Its dry season rainfall is underestimated and the length of the dry season overestimated by one to two months relative to observations. The GISS-ER underestimates clouds during the wet season leading to an overestimation of surface solar flux and surface sensible flux. This may cause the underestimation of rainfall in the 20th century simulation, and presumably may also influence the 21st century rainfall changes.

[41] Land surface fluxes control the initiation of the transition from dry to wet season [Li and Fu, 2004]. How soil moisture and the partitioning between sensible and latent heat fluxes are related to changes of surface radiative flux is important for determining the wet season onset and the length of the dry season. In both UKMO-HadCM3 and GISS-ER models, during the dry season, surface sensible heat flux is substantially overestimated and latent heat flux underestimated, leading to a Bowen ratio two- to three-times higher than that observed. The surface fluxes evidently are not sufficiently linked to deep soil moisture as observed in the Amazon [Nepstad et al., 2001]. Thus, the drying and delay of wet season onset may be overestimated in the UKMO-HadCM3 21st century simulation. Because the relative amplitude of seasonal change of total column soil moisture in both UKMO-HadCM3 and GISS-ER appear to be similar to that observed, a closer link between surface sensible and latent heat fluxes and deeper soil moisture would help to reduce the dry biases that currently exist in these models.

4.2. What Is the Possible Regional Impact?

[42] In the 20th century, the length of the dry season in most of the Amazon is less than four months. This is optimal for high aboveground biomass productivity and gross timber volume [Sombroek, 1966; Brown and Lugo, 1992]. In the central equatorial Amazon and south-central Amazon, the length of the dry season is about four to five months, close to the limit for sustaining rainforest. UKMO-HadCM3 predicts a two- to three-month increase of dry season length in the equatorial Amazon, which would increase the length of the dry season in the central equatorial Amazon to six to eight months. Such a long dry season would significantly increase the risk of “accidental” extensive forest fires and change the rainfall climatology to a regime suitable for savanna [Sombroek, 2001; Baker et al., 2004] in the central Amazon, as predicted by Cox et al. [2000]. The 10–15% reduction of wet season rainfall would also reduce the area of wetland, river discharge, and soil respiration. In the western Amazon, the length of dry season would increase to four to five months. Such a change could be more desirable for commercially viable agriculture settlement (given favorable soil conditions), highway construction, and the timber industry [Sombroek, 2001] and could consequently encourage more rapid and extensive land use in the western Amazon.

[43] The GISS-ER 21st century simulation predicts only small changes in the length of dry season. It may become one- to two-months longer over the northern Amazon, but one month shorter over the southern Amazon and Nordeste region. Thus, the seasonality of the rainfall would be favorable for rainforest in the southern Amazon and support a greener Nordeste region. Wet season rainfall would increase, especially over the eastern and southern Amazon. River discharge could increase over those regions. Overall, the climate impact on ecosystem and agriculture would be smaller than those implied by climate change predicted by the UKMO-HadCM3 simulations.

5. Conclusions

[44] We have analyzed changes of rainfall and its seasonality over the Amazon as part of global climate changes predicted by 11 models participating in the IPCC AR4. Under the SRES A1B scenario, five of these models (CNRM-CM3, GISS-EH, GISS-ER, IPSL-CM4, and NCAR-CCSM3) predict an increase of annual rainfall, three models (UKMO-HadCM3, GFDL-CM2.1, and MIROC3.2-medium resolution) predict a decrease of rainfall, and the other three models (INM-CM3.0, ECHAM5/MPI-OM, and MRI-CGCM2.3.2) predict no significant changes in the Amazon rainfall. Two models (UKMO-HadCM3 and ECHAM5/MPI-OM) also predict a greater interannual variation of the annual rainfall.

[45] To understand possible causes for different rainfall changes among these models, we have examined two models that are among the best in representing the rainfall seasonality over the Amazon based on observations between 1970 and 1999. Yet they predict opposite rainfall change. The UKMO-HadCM3 model predicts by 2101–2130 a decrease in rainfall of 10–15% during wet and transition seasons (August to March) and a one- to three-month increase in the length of the dry season. Its decrease of wet season rainfall appears to be caused by El Niño-like SST changes and by warming in the northern tropical Atlantic. These external climate changes enhance atmospheric subsidence and consequently stabilize the middle troposphere and reduce clouds over the Amazon. The resultant increase of surface solar absorption causes a stronger surface sensible heat flux. These changes reduce relative humidity of the near surface air and raise the level of free convection, presumably contributing further to the decreases of the wet season rainfall and surface latent heat flux. Decreased wet season rainfall leads to drier soil during the subsequent dry season, and thus less surface latent heat flux, more sensible heat flux, and a delay of the transition from the dry to wet season. Because large-scale moisture transport to the Amazon does not change significantly, the rainfall reduction is mainly caused by increases of subsidence. It results in more surface solar heating. The reduction of land surface latent heat flux and increase in sensible heat flux may provide a positive feedback and further reduce rainfall.

[46] In the GISS-ER model, the wet season rainfall increases by about 10%, and the dry season shortens by about a month in the southern Amazon and Nordeste regions. During the wet season, a warming in the western Pacific and the southern tropical Atlantic increases moisture transport and hence rainfall in the Amazon. The resultant higher soil moisture supports a higher surface latent heat flux during the dry and transition seasons, and may lead to the earlier wet season onset.
The UKMO-HadCM3 model has too little rainfall and surface latent heat flux during the dry season, presumably caused by its excessive moisture divergence. The latter transports out of the Amazon whatever moisture is provided by ET, consequently reducing rainfall, surface latent heat flux, and clouds. The decrease of clouds leads to excessive surface solar flux and sensible heat flux. These dry biases may contribute to the delay of wet season onset in the 20th century and to the predicted rainfall changes for the period of 2101–2130. The GISS-ER model underestimates late wet season moisture convergence and rainfall. Solar absorption and sensible heat fluxes at the surface are excessive throughout the year, even when rainfall and moisture agree with observations.

The strong reduction of rainfall predicted by the UKMO-HadCM3 model suggests a very high future risk of extensive forest fires and a climate more accessible for highway construction and commercialized farming in large parts of the western equatorial Amazon. The predicted long dry season in the eastern equatorial Amazon could change forest to savanna. The GISS-ER model, on the other hand, predicts a wetter climate over the Amazon and a shorter dry season in the southern Amazon and the Nordeste region, implying a higher river discharge and greater flooded areas in the Amazon and perhaps a greener Nordeste region.

Acknowledgments. We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modeling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy. We acknowledge use of the LBA Beija-flor search data set at http://beija-flor.ornl.gov/lba/. We thank Brant Liebmann and Dave Allured for kindly sharing the rain-gauge data over tropical South America with us, Katia Fernandes for helping with the LBA observational data, Zengyu Liu, Wanru Wu, Hui Wang, Jiping Liu, Shan Sun, and Haishan Chen for insightful discussions, and Susan Ryan for her editorial assistance. We thank the three anonymous reviewers for their constructive comments. This work is supported by NSF grant ATM-0203761 and the NOAA Pan American Climate Study Program.

References


Li, W., and R. Fu (2004), Transition of the large-scale atmospheric and land surface conditions from dry to wet season over Amazonia as diagnosed by the TCMWF Re-analysis, J. Clim., 17, 2037–2051.

Liebmann, B., and J. A. Marengo (2001), Interannual variability of the rainy season and rainfall in the Brazilian Amazon Basin, J. Clim., 14, 4308–4318.


R. E. Dickinson, R. Fu, and W. Li, Earth and Atmospheric Sciences, Georgia Institute of Technology, Ford ES&T Bldg., 311 Ferst Drive, Atlanta, GA 30332-0340, USA. (wenhong@eas.gatech.edu)