Climatic Change (2011) 106:285–302
DOI 10.1007/s10584-010-9902-x

Greenhouse gas induced changes in the fire risk in Brazil in ECHAM5/MPI-OM coupled climate model

Flavio Justino · A. S. de Mélo · A. Setzer · R. Sismanoglu · G. C. Sediyama · G. A. Ribeiro · J. P. Machado · A. Sterl

Received: 20 July 2009 / Accepted: 15 June 2010 / Published online: 24 August 2010

Abstract Vegetation fires are the second largest source of greenhouse gas emissions to the atmosphere. The reduction of the climatic impact of these emissions is related to the vegetation susceptibility to fire (fire risk), as well as to the understanding of possible implications of changes in atmospheric circulation on fire risk in the near-future. This study evaluates the environmental susceptibility to fire occurrence based on a Potential Fire Index (PFI). Two climate simulations from the ECHAM5/MPI-OM climate model have been used to calculate the PFI: present day (1980–2000) and an experiment for the end of the twenty-first century (2080–2100). The results indicate that the proposed PFI methodology could properly reproduce the areas with the highest fire incidence under present conditions. Moreover, it was found that under greenhouse warming conditions the PFI foresees an increase in the fire risk area, particularly for the Amazon region. We concluded, furthermore, that changes of vegetation predicted to occur in the future lead to substantial modifications in the magnitude of the PFI, and may potentially extend the length of the fire season due to induced longer drought periods as compared to current conditions.

F. Justino (✉) · A. S. de Mélo · G. C. Sediyama · J. P. Machado
Departamento de Engenharia Agrícola, Universidade Federal de Viçosa, Viçosa, Brazil
e-mail: fjustino@ufv.br

A. Setzer · R. Sismanoglu
Centro de Previsão de Tempo e Estudos Climáticas, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil

G. A. Ribeiro
Departamento de Engenharia Florestal, Universidade Federal de Viçosa, Viçosa, Brazil

A. Sterl
Climate Research & Seismology, Global Climate, Royal Netherlands Meteorological Institute, P.O. Box 201, 3730 AE De Bilt, The Netherlands

1 Introduction

It has long been documented that a close relation between mankind activities and the environment exists due to the influence of climate variations on the social well-being. The increase in consumption demands associated with the population growth over the last 10,000 years, has lead to substantial expansion of agricultural activities. Agriculture requires a seasonal management of the soil, which often involves the use of fire. According to Bar-Yosef (2002), during the evolution of man fire was used in the most remote regions. However, in recent decades various sectors of society have expressed preoccupation with the indiscriminate use of fire. Burning of biomass in ecosystems due to expansion of the agricultural frontier, conversion of forests into pastures and the renovation of agricultural land, are some of the most important factors in Brazil which cause impacts on the climate and biodiversity (Kirchoff 1997; Costa et al. 2007). Fires also cause impoverishment of the soil, destruction of vegetation, erosion problems and are linked to alterations in the chemical composition of the atmosphere (Aragão et al. 2007; Alencar et al. 2004; Crutzen and Andreae 1990; Saldarriaga and West 1986; Sanford et al. 1985).

Forest fires are not always directly attributed to human actions (Scott and Glasspool 2006). Fire occurrence is determined by factors which start the combustion reaction and that allows its continuation depending on the potential energy stored in the combustible material. For example, pollen studies in the central region of the Brazilian tropical savanna indicate the presence of charcoal in reconstruction which dates back 32,000 years (Ferraz-Vicentini 1999; Salgado-Labouriau and Ferraz-Vicentini 1994). This period, during the last ice age, between 100,000 to 10,000 years, is characterized by a cold and dry climate as compared to today (Justino and Peltier 2008; Cruz et al. 2005). However, very little is known about the causes which induced these fire susceptible conditions during this period, with lightening and natural fire associated with the dryness of the vegetation and the reduced atmospheric CO_2 concentration assumed as the most probable ignition cause (Ehleringer et al. 1997).

The environmental conditions of recently burnt regions reinforce the behaviuor which favor the ignition of new fires (Ribeiro and Bonfim 2000). During the first stage of deforestation, the large and valuable trees are removed. These changes may alter the microclimate favouring the occurrence of future fires. Among the risks associated with the levelling of large areas of the forests, modification of the hydrological cycle with the reduction of evapotranspiration stands out (Cook and Vizy 2008). On a large scale this reduces the recycling of atmospheric water vapor and eventually causes reductions in precipitation. Additionally, heavy smoke from forest fires in the Amazon is observed to reduce cloud droplet size and so delay the onset of precipitation (Andreae et al. 2004).

Impacts of vegetation fires are prominent in questions involving future climate changes, especially regarding the intensification of Global Warming (Bowman et al. 2009; Golding and Betts 2008). Vegetation fires on a global scale are the second largest source of greenhouse gas emissions. For example, the amount of carbon dioxide (CO_2) released in Indonesian fires in 1997 and 1998 was equivalent to 25% of the total global CO_2 emissions due to the combustion of fossil fuels (Page et al. 1997). In Brazil, vegetation fires are responsible for roughly 60–70% of CO_2 emissions to the atmosphere, yet despite its scientific and social relevance, the link between climate conditions and fire risk has not been extensively investigated in Brazil. This is done in North America, for example, by the use of the Haines Index (HI), which however does not take into account the characteristics of the vegetation cover.

Several indices have been proposed to investigate the atmospheric susceptibility to vegetation fires. In Brazil, the most utilized are the: Angstrom index, Telicyn Logometric index, Nesterov index, Altered Monte Alegre (FMA+), RisQue (Nepstad et al. 2004), and the CPTEC-INPE (2009). Currently, the greatest incidence of vegetation fires in the central part of South America occurs from August to November, with a peak in September (Sismanoglu et al. 2002; Justino et al. 2002). This seasonal maximum is directly associated with the dry period that proceeds the rainy planting season (Fig. 1a).

An important step for reducing the impacts of forest fires on climatic and social conditions is the investigation of the environmental susceptibility to wildfire (fire risk). Vera et al. (2006), using future precipitation projections for the period 2070–2099 in South America, found a reduction in precipitation during the winter over almost the entire continent and a reduction in precipitation throughout the year in the southern region of the Andes. Moreover, Cook and Vizy (2008), based on regional climate models coupled with a vegetation potential model, suggest that by the end of the twenty-first century 70% of the Amazon forest will be replaced by

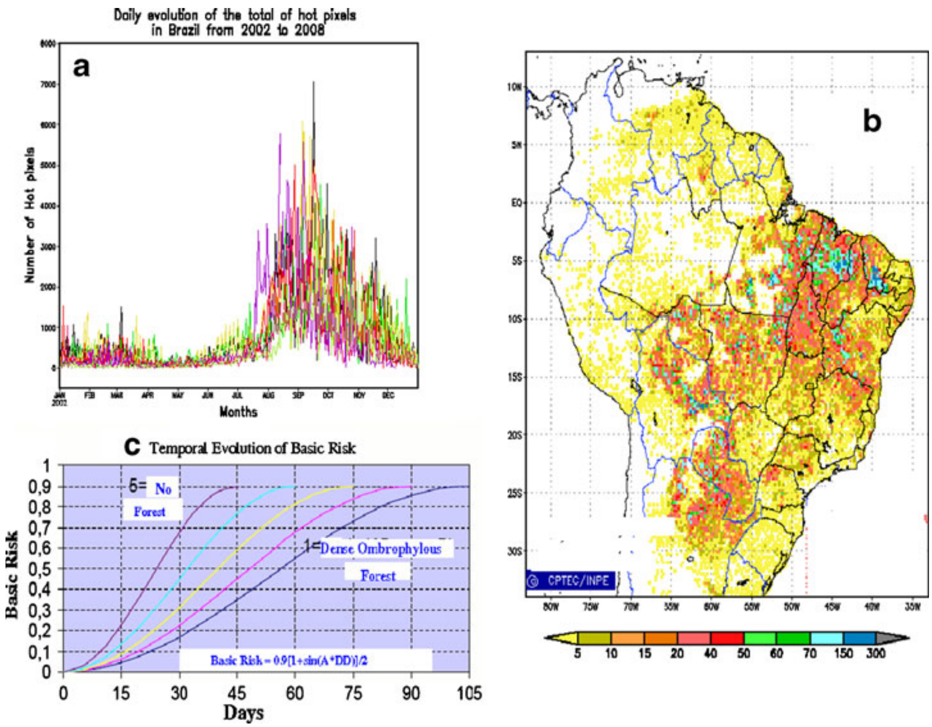

Fig. 1 (**a**) Daily evolution of the vegetation fires in Brazil from 2002 to 2008. (**b**) Spatial distribution of vegetation fires in South America in 2008 as monitored by satellites, a year with relatively few events (INPE 2009). The scale indicates the number of fire pixels per grid cell of 25 km by 25 km. (**c**) Temporal evolution of basic risk as function of the days of drought and vegetation

savanna. These findings raise questions regarding the potential impact of twenty-first Century climate and vegetation change on increasing atmospheric susceptibility to wildfire occurrence.

Climate simulations have demonstrated that reduced precipitation and higher temperature may accelerate the dieback of the Amazon rainforest (Cook and Vizy 2008; Salazar et al. 2007). This process leads to the increase of canopy openness and under-storey insolation with consequent drying of the accumulated litter. When these conditions are combined, the risk of forest fires can increase dramatically in Amazonia (Barlow and Peres 2004; Nepstad et al. 2004). Recently, Golding and Betts (2008) used the McArthur Forest Fire Danger Index and an ensemble of variants of the HadCM3 climate model to simulate potential changes to fire risk in Amazonia over the twenty-first century. They showed that significant increases in central and eastern Amazonia are predicted by 2020, and that high fire danger for over 50% of the forest is simulated in all model runs by 2080. Bond et al. (2004) highlighted the level of importance of fire in determining global vegetation patterns by preventing ecosystems from achieving the potential height, biomass and dominant functional types.

The present study proposes a further evaluation of the atmospheric favorability to the occurrence of vegetation fire. This shall hereafter be referred to as Potential Fire Index (PFI), based upon a new methodology which takes into account the daily values of maximum temperature (tmax), precipitation (prec), vegetation types and the minimum relative humidity (URmin). Precipitation is included as a drought factor which is calculated using daily rainfall. The paper is organized as follows: Sections 2 and 3 describe the coupled atmosphere–ocean–sea-ice model, and the design of the climate experiments to be analyzed. Section 3 also includes the methodology to compute the PFI, and Section 4 summarizes our main findings.

2 Data and methodology

2.1 Climate data

In order to compute the PFI for present day (PD) and greenhouse warming (GW) conditions, two climate simulations have been utilized. To model the atmospheric susceptibility to fire occurrence under PD and GW conditions, we have used data from the ESSENCE project (Sterl et al. 2008, www.knmi.nl/~sterl/Essence) based on the ECHAM5/MPI-OM coupled climate model. The two components of the model, ECHAM5 for the atmosphere and MPI-OM for the ocean, are well documented (Jungclaus et al. 2006). The version used here is the same as that adopted for climate scenario runs in preparation of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (AR4-IPCC). ECHAM5 is run at a horizontal resolution of T63 and 31 vertical hybrid levels with the top level at 10 hPa. The ocean model MPI-OM is a primitive equation z-coordinate model with a variable horizontal resolution. The baseline simulation period is 1950–2100. For the historical part (1950–2000) the concentrations of greenhouse gases (GHG) and tropospheric sulfate aerosols are specified from observations, while for the future part (2001–2100) they follow the SRES A1b scenario (Nakicenovic et al. 2000). The A1b storyline describes a world of very rapid economic growth, low population growth, and rapid

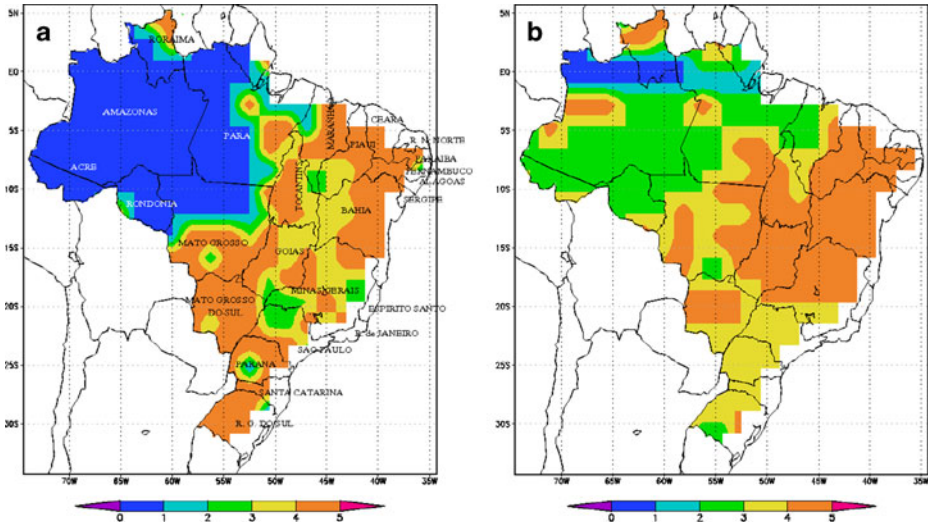

Fig. 2 Vegetation distribution for present day (**a**) and under greenhouse warming conditions (**b**), but converted to A values used in Eq. 13. Brazilian state names are included. Adapted from Cook and Vizy (2008)

introduction of new and more efficient technologies. The A1b is a moderate resource user with a balanced use of technologies. This scenario projects the description of a future state of emissions of the principal greenhouse gases and aerosols. In the ESSENCE project 14 species of GHGs are included. Besides CO_2, there are CH_4, N_2O, and 11 different CFCs. For the intermediate A1B scenario, the atmospheric concentration of CO_2 is a little more than 700 ppmv (parts per million by volume) for the end of the twenty-first century.

2.2 Vegetation data

The scientific community has been intrigued for decades with the challenge of investigating global changes, particularly predicting the future of vegetation distribution (Cook and Vizy 2008; Salazar et al. 2007). This possible change in vegetation, either by natural or anthropogenic actions, could cause a substantial modification of the climate, not only locally but also regionally and globally (Charney et al. 1977; Sud and Fennesy 1982, 1984; Xue and Shukla 1993, 1996; Dirmeyer and Shukla 1996; Oyama 2002; Cook and Vizy 2008). To evaluate the PFI under present day and greenhouse warming conditions we have utilized two vegetation cover projections as proposed by Cook and Vizy (2008). They argue that by the end of the twenty-first century 70% of the Amazon forest will be replaced by savanna (Fig. 2). In the case of "savannization" of the Amazon, one may ask what effect will this have.

3 Formulation of the potential fire index

The PFI methodology is based on the temporal and spatial empirical evidence of the occurrence of hundreds of thousands of vegetation fires in Brazil (Brown et al.

2006) during the last 20 years. Even though the vast majority of these fires are of anthropogenic origin and spread over most of the country (see Fig. 1b), they are related to the annual climate cycle since the purpose of the burnings is a fast and efficient removal of the natural vegetation, which generally is for agricultural purposes. The PFI tends to simulate the phenology of different vegetation covers, and shows an increase as the dry season progresses, incorporating the amount and distribution of rains, maximum air temperatures, and minimum relative humidity. The reference of the calculations is the nominal "Number of Dry Days" or "Days of Drought" (DD), which is a hypothetical number of consecutive days without precipitation, which are obtained by periods during the precedent 120 days in relation to the date of the PFI calculation. This index is produced and operationally used in real-time for Brazil and other countries in South America to provide the potential risk of wildfire development. Continuous updates of its skill are available, with over 90% success during the dry/fire seasons. Products and detailed information is available at CPTEC-INPE (2009) and INPE (2009).

3.1 Sequence of the PFI calculation

1. Determine daily for a given geographic area, the value of precipitation, in millimeters (mm) accumulated for the 11 immediately preceding periods of 1, 2, 3, 4, 5, 6–10, 11–15, 16–30, 31–60, 61–90 and 91–120 days.
2. Calculate the "Precipitation Factors" (PF) with values ranging from 0 to 1 for each of the 11 periods, using an empirical exponential function of the precipitation in millimeters for each period. The respective equations used are:

$$PF_1 = \exp(-0{,}14\mathrm{Prec}) \tag{1}$$

$$PF_2 = \exp(-0{,}07\mathrm{Prec}) \tag{2}$$

$$PF_3 = \exp(-0{,}04\mathrm{Prec}) \tag{3}$$

$$PF_4 = \exp(-0{,}03\mathrm{Prec}) \tag{4}$$

$$PF_5 = \exp(-0{,}02\mathrm{Prec}) \tag{5}$$

$$PF_{6\_10} = \exp(-0{,}01\mathrm{Prec}) \tag{6}$$

$$PF_{11\_15} = \exp(-0{,}008\mathrm{Prec}) \tag{7}$$

$$PF_{16\_30} = \exp(-0{,}004\mathrm{Prec}) \tag{8}$$

$$PF_{31\_60} = \exp(-0{,}002\mathrm{Prec}) \tag{9}$$

$$PF_{61\_90} = \exp(-0{,}001\mathrm{Prec}) \tag{10}$$

$$PF_{91\_120} = \exp(-0{,}0007\mathrm{Prec}) \tag{11}$$

3. Calculate the "Days of Drought" (DD) according to the equation:

$$DD = 105 \times \left(PF_1 \times \ldots \times PF_{91\_120}\right) \tag{12}$$

4. Determine the basic potential fire (BR) for each of the five types of vegetation considered, using the equation:

$$BR_{n-1,5} = 0,9 \times \left(1 + \sin\left(A_{n-1,5} \times DD\right)\right)/2 \tag{13}$$

The $A_{1,5}$ stands for the types of vegetation (Table 1). Based on Eq. 13, low values of A are indications that the vegetation needs a longer period without precipitation to reach the maximum BR. For instance, regions covered by non-forests would experience high BR under 45 days of drought whereas areas covered by evergreen forests would need 95 days of drought to deliver similar BR. Figure 1c illustrates the variation of the BR using the previously defined equations and concepts. It should be noted that the "days without rain" axis, indicates both the real period of days without rain as well as the "days of drought (DD)", which corresponds to a hypothetical period without rain calculated from the temporal quantity and distribution of occurred rains. One may assume that the periods of "days without rain" or "days of drought" make up the basic principle of this method.

Afterwards, two other factors are also considered for calculation of the final fire risk (PFI). Firstly, the BR is corrected based on the minimum relative humidity of the air. The risk (RH) increases when humidity is less than 40% and diminishes for values greater than 40%. Humidity data from observations during the 18 h GMT are used, in search of the minimum value. The linear adjustment equation is:

$$RH = BR \times (-0{,}006RH_{min} + 1{,}3) \tag{14}$$

Secondly, the fire risk is corrected based on the maximum temperature of the air. The risk (RT) increases for temperatures higher than 30°C and decreases for temperatures lower than 30°C. Temperature data from observations during the 18 h GMT are used, in search of the maximum value. The linear adjustment equation is:

$$RT = RH \times (0{,}02T_{max} + 0{,}4) \tag{15}$$

After performing the necessary calculations, the PFI attains values between 0 and 1, in the following categories:

Table 1 Classes of fire risk

Risk level	PFI (0 to 1)
Minimum	0–0,15
Low	0,15–0,40
Medium	0,40–0,70
High	0,70–0,90
Critical	> 0.90

4 Results and discussions

In order to investigate the impact of the inclusion of greenhouse warming conditions on fire susceptibility in Brazil, three evaluations were performed: The first investigated fire risk is based on the current climate as predicted by ECHAM5/MPI-OM and vegetation according the PD simulation of Cook and Vizy (2008). The second analysis was performed for future climate conditions (2080–2100) and disregarded changes in vegetation, using the current biome distribution (Fig. 3a). The third calculation uses results of the ECHAM5/MPI-OM GW simulation and the future vegetation distribution (Fig. 3b). Climate anomalies between PD and GW simulation have been extensively discussed by Sterl et al. (2008) and no purpose will be served by discussing this in detail herein.

The ECHAM5/MPI-OM simulated reasonably well the seasonal cycle in terms of temperature, precipitation and relative humidity (Lin et al. 2006; Liebmann et al. 2004) as compared to the NCEP Reanalysis. Since the results here are presented for each month from June to October, a brief analysis of the seasonal cycle of both dataset (ECHAM5/MPI-OM and NCEP) in terms of amplitude of the seasonal cycle is provided below based on harmonic analysis.

The harmonic analysis is a useful tool to identify areas with large seasonal variability and may demonstrate regions with distinct temperature and precipitation changes throughout the year. This may be noted in Fig. 3. The amplitude of the first harmonic of near surface air temperature (t2m) for NCEP (Fig. 3a) shows that the largest seasonal changes of t2m is located over the southern part of Brazil, with values as high as 6°C. On the other hand, small changes are noted over the Amazon region. Analysis for the ECHAM5/MPI-OM t2m shows a second area with high seasonal changes over the central part of the country (Fig. 3b), which has not been reproduced by the NCEP dataset.

Turning to investigation of the amplitude of the 1st harmonic of precipitation (Fig. 3c, d) one may note many similarities between both datasets. However, differences may be verified primarily over the north portion of the Amazon region. The highlighted feature is the largest seasonal variability over the central part of Brazil which reveals the dominance of two defined seasons. The dry season from June to October and the rainy season from November to May. It is during the former period that the region experiences the highest incidence of fire. As might be anticipated, analyses to relativity humidity (Fig. 3e, f) fit very closely the results of precipitation. Indeed, the central part of Brazil is dominated by high seasonal changes of relative humidity, with amplitude as high as 30%.

In what follows the monthly evolution of the PFI as well as its components are shown. It should be noted that since the largest number of vegetation fires in Brazil occur between June and October, the analyses conducted here are restricted to these months. One may note that for the future period we use projected future vegetation which has not been included in the ESSENCE climate simulations as boundary conditions. These conditions provide a strengthening of the atmospheric susceptibility to fire occurrence. Therefore, the following evaluation discussed here may provide a weaker response of the vegetation fire vulnerability to climate change, since this two-ways link between vegetation-climate-vegetation is not included interactively in the ECHAM5/MPI-OM model.

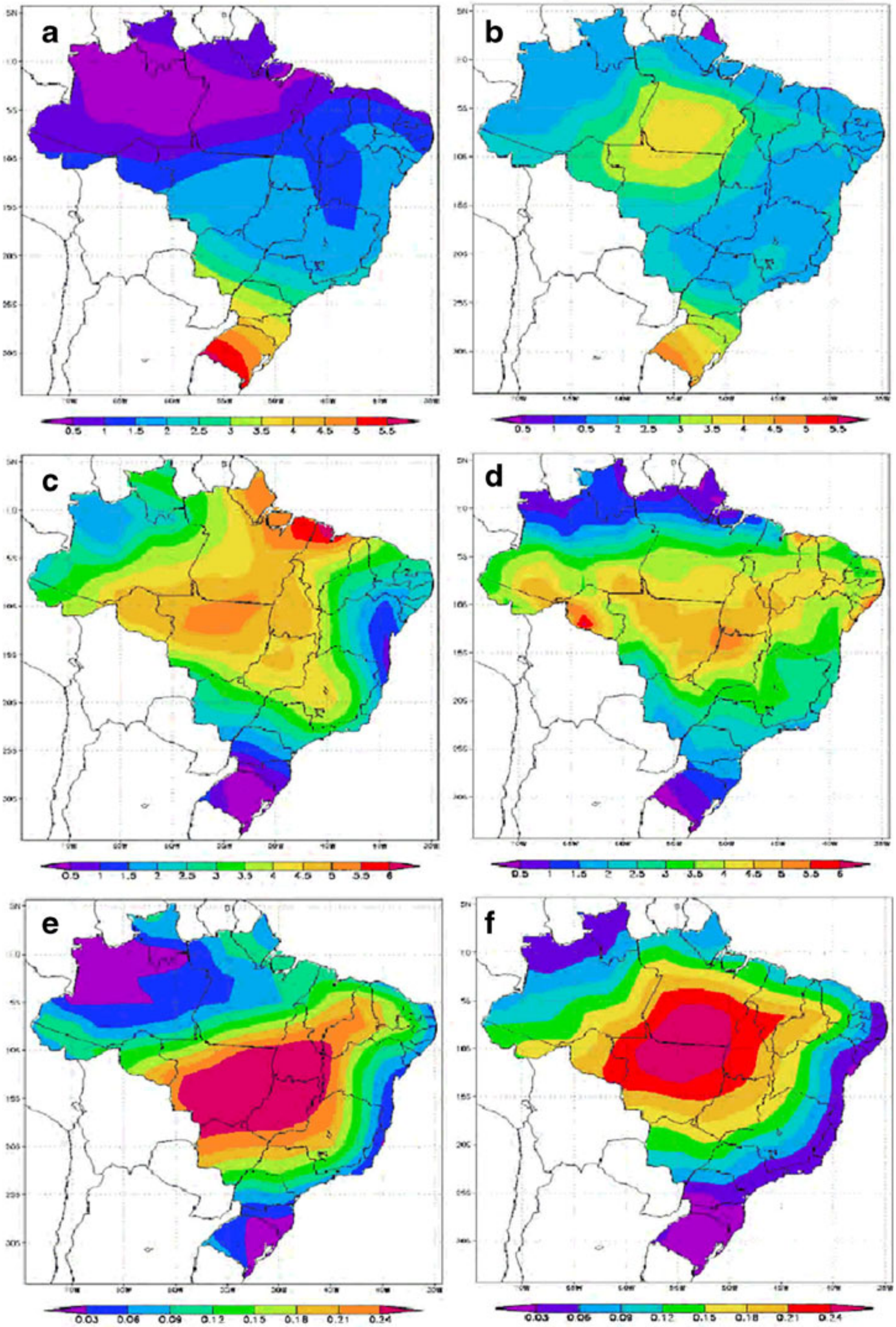

Fig. 3 Annual amplitude of the first harmonic. (**a**) Temperature from NCEP reanalyses. (**b**) Temperature from PD simulation. (**c**) Precipitation from NCEP reanalyses. (**d**) Precipitation from PD simulation. (**e**) Relative humidity from NCEP reanalyses. (**f**) Relative humidity from PD simulation

4.1 Analysis for the month of June

Figure 4 shows the present day simulated maximum temperature (Tmax), the minimum relative humidity (Rhmin), and the drought days (DD) as defined by the Eq. 13. Under present day conditions one may note that in June the highest Tmax occurs in the northern part of Brazil (Fig. 4a). In terms of Rhmin it is clear that in the most part of Brazil, the Rhmin is above 80%. June is the beginning of the dry season for central South America and there still exists considerable amount of water vapour

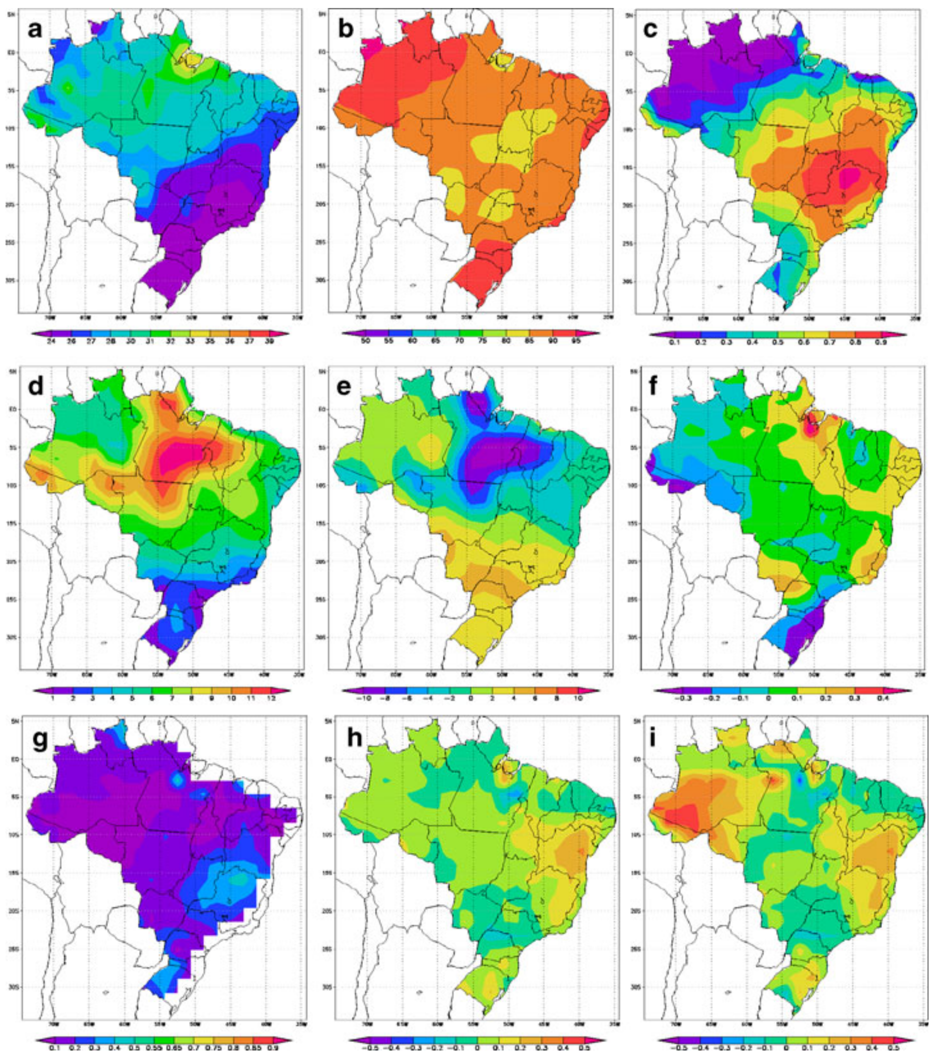

Fig. 4 Monthly mean conditions in June. (**a**) Maximum temperature, (**b**) minimum relative humidity, (**c**) days of drought, (**d**) maximum temperature anomalies, (**e**) minimum relative humidity anomalies, (**f**) days of drought anomalies between GW and PD simulations. (**g**) Potential fire index (PFI) for present day conditions, (**h**) PFI anomalies between GW and PD simulation with present day vegetation, (**i**) PFI anomalies between GW and PD simulation but with future vegetation

in the atmosphere (Fig. 4b). Analysis for the DD (days of drought) shows a large area with values higher than 0.7 over the central and south-eastern part of Brazil, whereas lower DD are depicted over the Amazon region. As shown in Fig. 4g, the combined effect of Tmax, Rhmin and DD (Eq. 12) is associated with low atmospheric favorability to wildfire development i.e. low PFI.

Turning to the investigation based on the GW simulation, we project a warming of roughly 10°C (Fig. 4d) over the north-central region of Brazil, accompanied by a reduction in the Rhmin by up to 10% (Fig. 4e), in comparison to the results from the PD simulation (Fig. 4a, b). Positive values of the DD index anomalies also indicate a longer period without rain (Fig. 4f). These expected anomalous climatic conditions favor an increase in the fire risk in comparison to current levels demonstrated by the intensification of the PFI (Fig. 4h). It should be noted that this analysis does not include changes in vegetation as predicted to occur by 2080–2100 (Cook and Vizy 2008). For this calculation vegetation remains as today's conditions.

The inclusion of the future vegetation data projects an intensification of the PFI which is entirely linked to the absence of the rainforest (Fig. 4i). The presence of savanna induces an increase in the basic risk (BR, Eq. 13) and consequently an increase in the PFI. It is also clear that the region from the State of Bahia to Minas Gerais (5° S–20° S, 55° W–43° W) will present a high PFI (Fig. 4i). This area under future conditions is expected to experience an expansion of savanna and "caatinga", with a higher A term, instead of pastures and shrubs which is currently the predominant biome. These results show the importance of the type of the vegetation cover for the atmospheric susceptibility to wildfire development.

4.2 Analysis for the month of July

In July there exists, an intensification of the atmospheric conditions which are more favorable to vegetation (Fig. 5). Indeed, the Tmax reaches values up to 33°C accompanied by a reduction in the Rhmin. Compared to June one may also find an increase in the area of critical DD values. This leads to the intensification of the PFI under PD conditions, in particular in the area called the arc of deforestation (a band along the eastern and southern edges of the forest in the States of Mato Grosso and Pará). Moreover, an enlargement in the area dominated by medium PFI in the south-eastern part of Brazil is identified (Fig. 5g).

Analyses based on GW conditions show that anomalies of maximum temperature between the future and current periods are up to 6°C. It is interesting to stress, furthermore, the increase of Rhmin over the Amazon region under future conditions (Fig. 5e). However, this increased water vapor availability is not converted into precipitation in order to cancel out the higher DD as compared to PD conditions, as shown in Fig. 4f. This leads to large changes in the PFI even if future changes of vegetation are not considered (Fig. 5h).

By including future vegetation cover a different picture emerges (Fig. 5i). The replacement of the rainforest by savannas induces an intensification of the PFI in most of the Amazon basin. Over the western part of the country, the higher flammability, than those of PD conditions, is primarily associated with the positive Tmax anomalies (Fig. 5d). This is since the projected changes of vegetation, i.e. the replacement of present day savannas by future decidual seasonal forest, would reduce the PFI due to smaller A factor related to the latter biome (Fig. 2, Eq. 13).

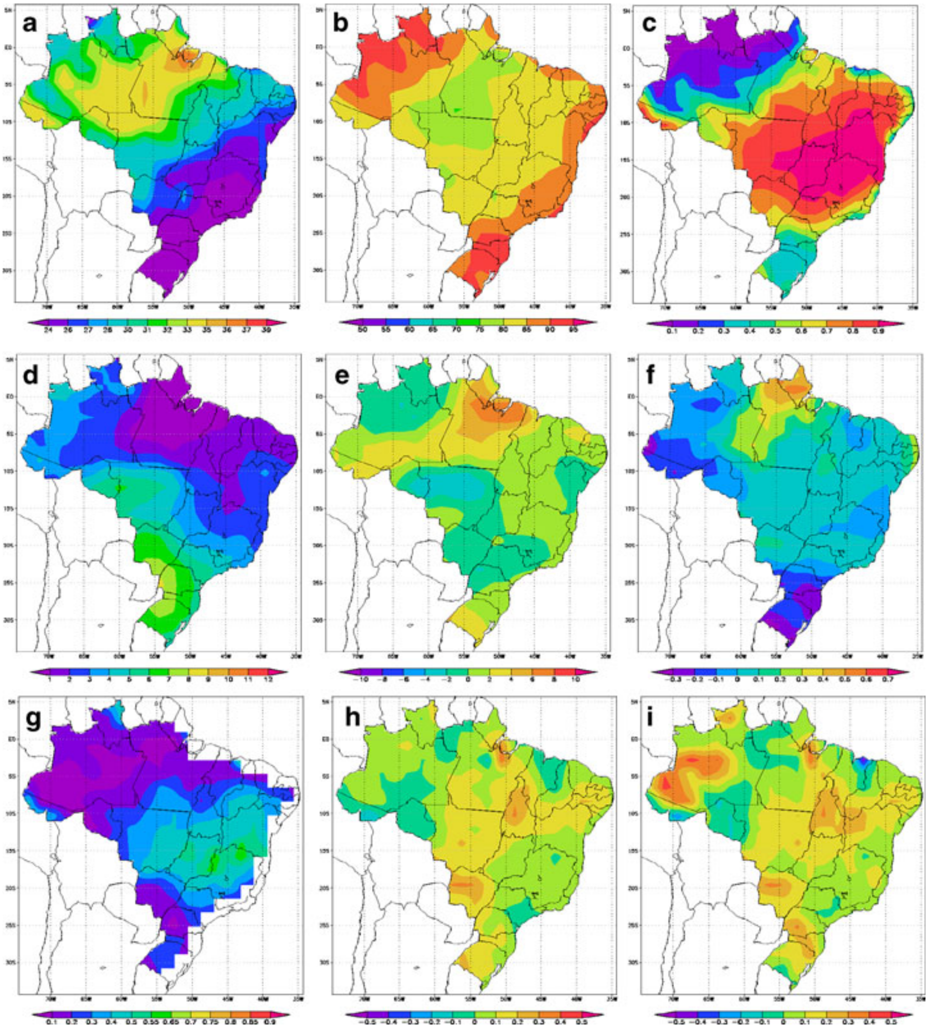

Fig. 5 Same as Fig. 3 but for July

4.3 Analysis for the month of August

According to Fig. 1, the highest incidence of fire in Brazil occurs from August to September in the central part of Brazil, in particular in northern Mato Grosso, Rondônia and southeast Pará. This matches very closely the greatest values of Tmax, lowest values of Rhmin and the long drought period (DD) (Fig. 6a, b, c). Evaluation of the PFI calculated based on current climatic conditions as simulated by the PD simulation, beckon the existence of fire risk in the central part of Brazil (Fig. 6g). It is interesting to note that in spite of the substantial area covered by critical values of DD, the influence of cold conditions in the winter season (except State of Amazonia) reduces the PFI substantially. The low PFI in Amazonia is also related to the low values of the DD (Fig. 6c).

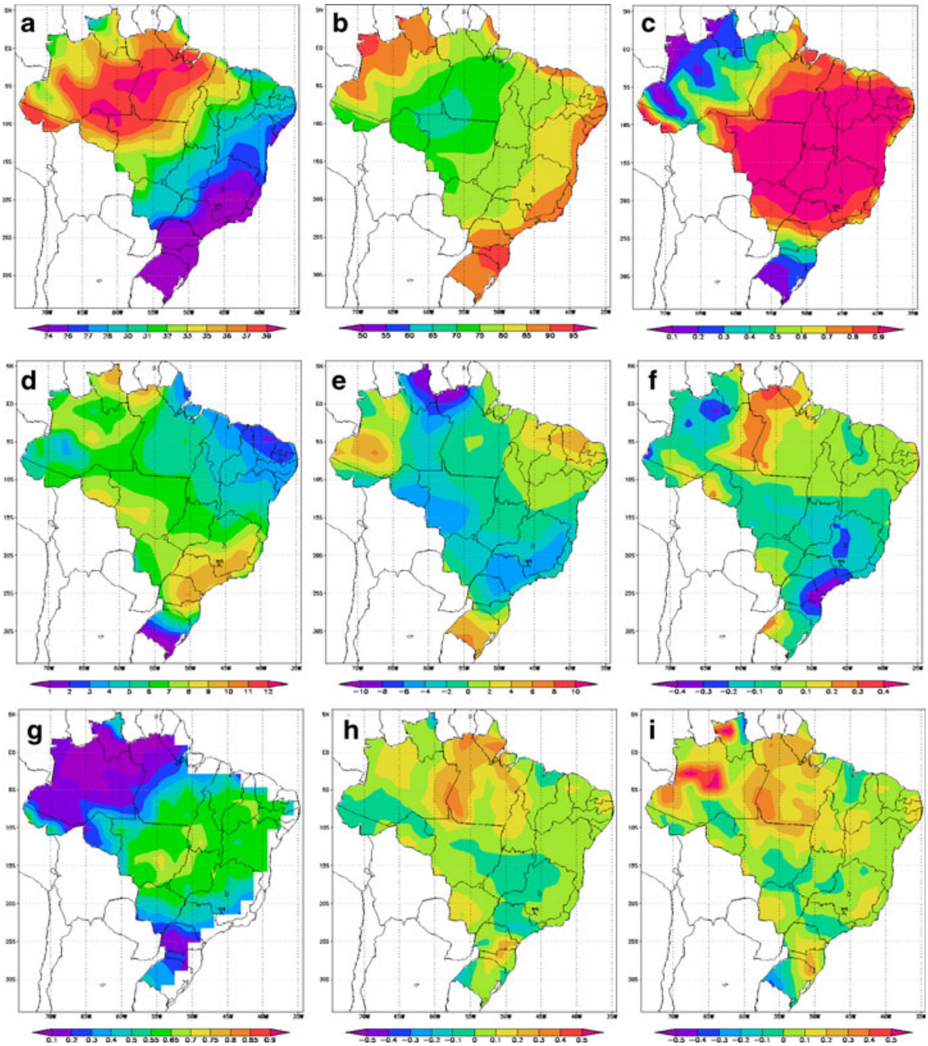

Fig. 6 Same as Fig. 3 but for August

Analysis for global warming conditions shows an intensification of fire susceptibility in the central part of Brazil and in particular in the Amazon basin (Fig. 6h). Calculations which include the projected vegetation for the end of the twenty-first century, show the migration of the area favorable to fire as compared to those of PD conditions. Moreover, it may be noted an intensification and enlargement in area of high PFI in respect to the PFI calculation based on present day vegetation (Fig. 6h, i). Under these conditions, the maximum PFI passes to include the north of Pará, Amazonas and Roraima. It is important to note that these areas, particularly the northeast of Pará, do not currently show a large number of fires being an area of dense forest with little human presence. However, for the future, this region is expected to be affected by the conversion of the native forest in savanna. On

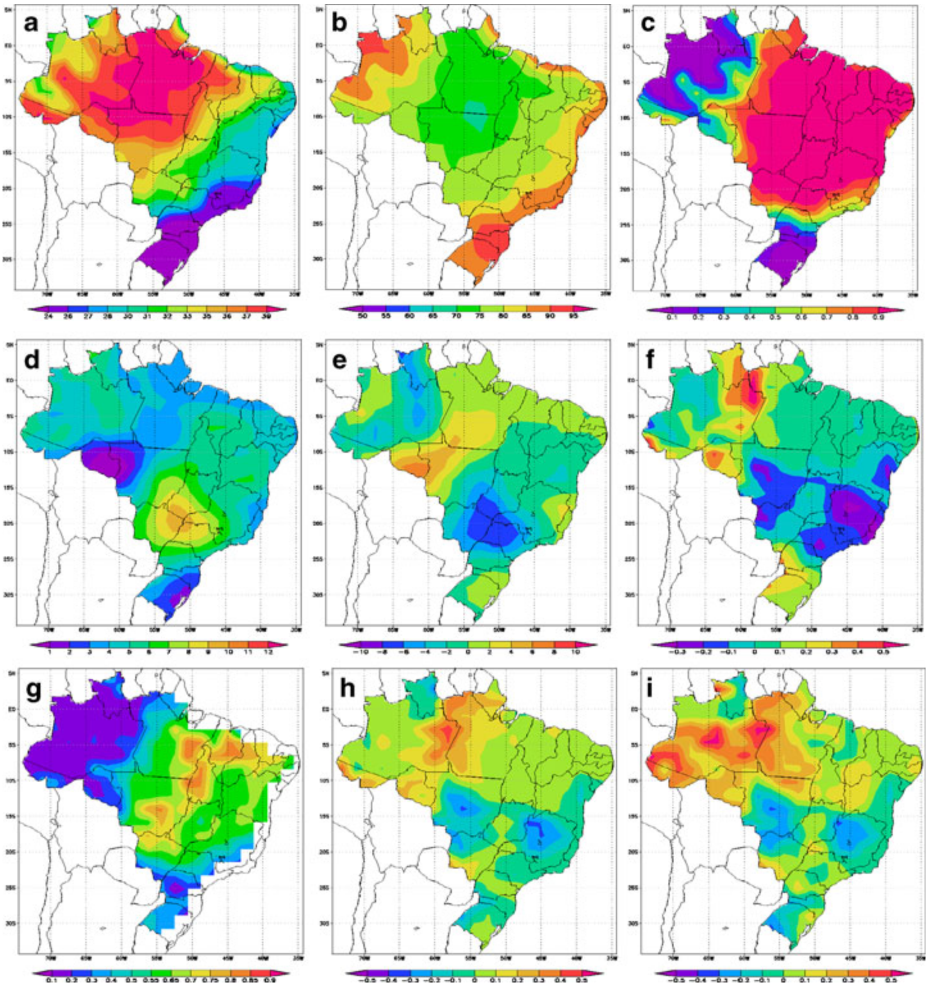

Fig. 7 Same as Fig. 3 but for September

the other hand, the presence of pastures, substituting savanna, is associated with a desintensification of the PFI in the State of Mato Grosso (Fig. 6i).

4.4 Analysis for the month of September

Climate conditions in September are more favorable to the occurrence of vegetation fires as compared to August (Fig. 7). High temperature, low relative humidity and the long absence of rain lead to an intensification of the PFI, in all areas except over the western Amazon basin (Fig. 7g). As for August, the central part of Brazil is the critical region, in particular the States of Mato Grosso, Pará and Maranhão. This result matches very closely the highest current fire activity in Brazil as detected by satellite (Fig. 1a). Turning to the investigation of the environmental susceptibility to fire under GW conditions, it is evident that the influence of induced low relative humidity, high temperatures and the high DD leads to the positive PFI anomalies.

For this month, the PFI associated with the inclusion of greenhouse forcing attains values up to 0.9, therefore projecting fire risk in the critical level (Fig. 7h). By combining the climate and vegetation as projected by 2080–2100 (Fig. 7i) one may note remarkable changes in the PFI, as compared to present conditions. The replacement of the rainforest by savannas in the States of Pará, Acre and Rondônia causes an increase in the PFI. However, in the States of Minas Gerais and Mato Grosso, the index associated with the days of drought decrease and changes in vegetation from present day savanna to mixed shrubland/grassland lead to lower atmospheric favorability to fire (Fig. 7i). In fact, during this month the South Atlantic Convergence Zone begins to act in the southeastern and central Brazil providing more frequent rains.

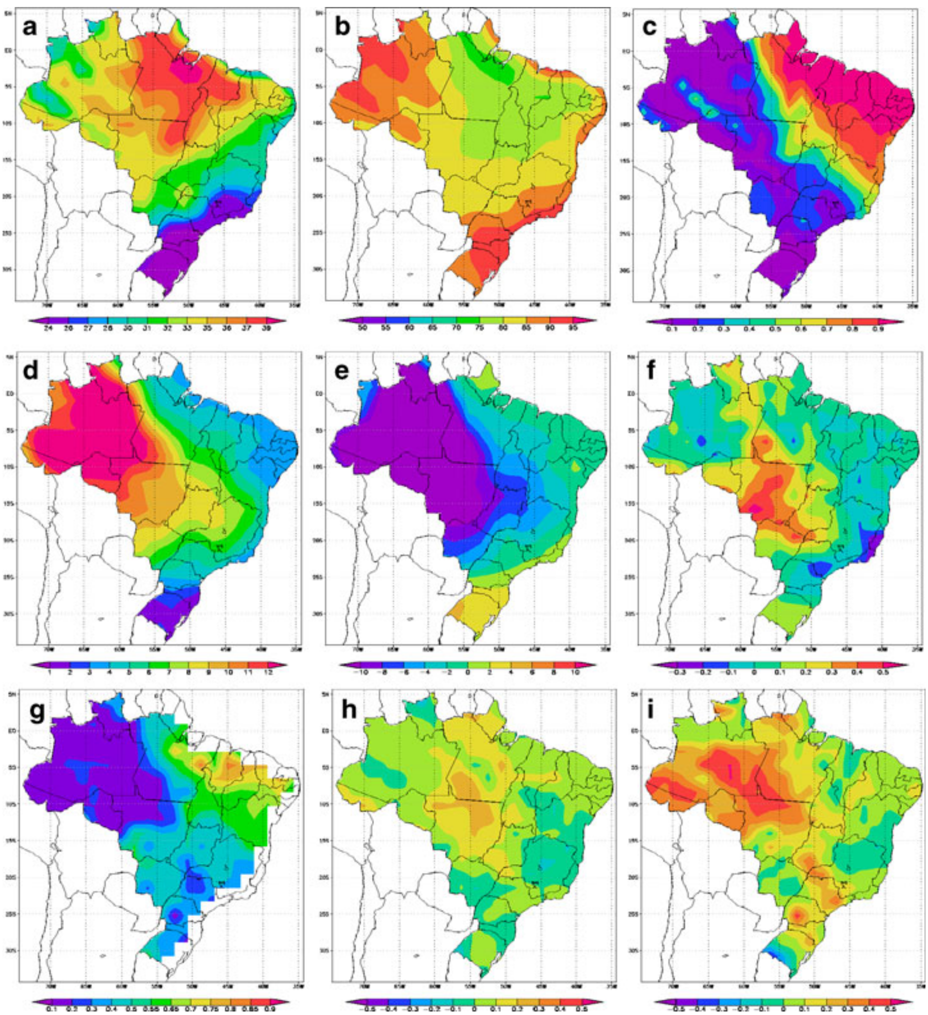

Fig. 8 Same as Fig. 3 but for October

4.5 Analysis for the month of October

October is the beginning of the rainy season for the majority of Brazil, when atmospheric conditions most favorable for vegetation fires are located in the north of the country (Fig. 8i). Analysis of the PFI follows, with tolerable limits, the anomalies of Tmax, Rhmin and DD (Fig. 8a, b, c). The low values of the DD term in the western part of Brazil should be highlighted. Moderate values are observed for the PFI in the northern portion of the States of Pará and Maranhão only (Fig. 8g). Future climate conditions induce an enhancement of the fire risk, particularly in the State of Mato Grosso and Pará, the latter showing in its north portion critical values of PFI (Fig. 8h). Figure 7i reveals that by including the projected future vegetation, the Amazon region will very likely be more suitable for large fire events.

Under present day conditions, in November the fire activity in Brazil begins to be reduced due to the onset of the rainy season. However, the calculated PFI from future conditions still exhibit considerable fire risk, in particular when the simulated future changes of vegetation are included (not shown). This implies that if the projected climate changes were confirmed in the future, the fire season may be longer throughout the year as compared to current conditions as proposed by Cook and Vizy (2008).

5 Conclusions

Based on multi-century climate simulation performed by the ECHAM5/MPI-OM coupled climate model, this study has evaluated the impacts of climate changes on vegetation-fire risks in Brazil under current and future global warming conditions. The investigation supports a new Potential Fire Index (PFI), which is computed from daily values of maximum temperature (Tmax), vegetation types and the minimum relative humidity (URmin). Precipitation is included as a drought factor that is calculated using daily rainfall. We demonstrated that the PFI was able to detect the principal fire risk areas which are concentrated in the central-west and north regions of Brazil from June to October.

Calculation of the PFI using the two different vegetation scenarios for current conditions and those proposed for global warming scenario, shows that the future PFI is extremely sensitive to the conditions imposed by the vegetation. When forest was substituted for savannas a greater fire risk was projected. Similarly, areas of savanna which were substituted for pastures showed lower PFI values. Thus, according to the anomalous atmospheric conditions predicted for the future, Brazil will be more favorable to large scale vegetation fires, principally in the Amazon region and in the northeastern portion of country. It should be noted that the PFI may be applied worldwide because it is based on vegetation and climate factors that are regionally dependent.

The results presented here are regarding natural fire occurrence based on climatic factors and therefore are entirely independent of the human action. One should note, however, that an increase in lightning incidence, an approximate 5–6% change in global lightning frequencies for every 1°C global warming as proposed by Price and Rind (1994), may cause a greater number of natural vegetation fires in the future. While these results are very useful, the majority of vegetation fires in Brazil are of anthropogenic origin and changes in the socio-economic and cultural structure of the region are likely to have a strong influence in the future. Despite this fact, it is crucial to have an assessment of the areas more favourable for fire development in the future, in particular to avoid the occurrence of erratic wildfire which may cause substantial reduction in the ecosystem diversity.

Acknowledgements The authors thank FAPEMIG for support through the grant CRA-PPM-00212-08. The ESSENCE project, lead by Wilco Hazeleger (KNMI) and Henk Dijkstra (UU/IMAU), was carried out with support of DEISA, HLRS, SARA and NCF (through NCF projects NRG-2006.06, CAVE-06-023 and SG-06-267). We thank the DEISA Consortium (co-funded by the EU, FP6 projects 508830/031513) for support within the DEISA Extreme Computing Initiative (www.deisa.org). The authors thank Camiel Severijns (KNMI), and HLRS and SARA staff for technical support. We are also grateful to Kerry Cook and Edward. Vizy for making available the vegetation data.

References

Andreae MO, Atlas E, Harris GW, Helas G, Koppmann R, Maenhaut W, Manõ S, Pollock WH, Rudolph J, Schaeffe D, Schebeske G, Welling M (1996) Methyl halide emissions from Savanna fires in Southern Africa. J Geophys Res 101:23603–23601

Andreae MO, Rosenfeld D, Artaxo P, Costa AA, Frank GP, Longo KM, Silva-Dias MAF (2004) Smoking rain clouds over the Amazon. Science 27:1337–1342

Alencar A, Solórzano L, Nepstad DC (2004) Modeling forest understory fire in an eastern Amazon landscape. Ecol Appl, USA 14(4):S139–S149

Aragão LEOC, Malhi Y, Roman-Cuesta RM, Saatchi S, Anderson LO, Shimabukuro YE (2007) Spatial patterns and fire response of recent Amazonian droughts. Geophys Res Lett 34:L07701. doi:10.1029/2006GL028946

Barlow J, Peres CA (2004) Ecological responses to el Niño-induced surface fires in central Brazilian Amazonia: management implications for flammable tropical forests. Philos Trans R Soc Lond B Biol Sci 359(1443):367–380

Bar-Yosef O (2002) The upper paleolithic revolution. Annu Rev Anthropol 31:363–393

Bond WJ, Woodward FI, Midgley GF (2004) The global distribution of ecosystems in a world without fire. New Phytol 165:525–538

Bowman DMJS et al (2009) Fire in the earth system. Science 324:481–484. doi:10.1126/science.1163886

Brown IF, Schroeder W, Setzer AW, De Los Rios Maldonado M, Pantoja N, Duarte A, Marengo J (2006) Monitoring fires in southwestern Amazonia rain forests. EOS transactions. American Geophysical Union 87:253–264

CPTEC-INPE (2009) Fire risk products. http://pirandira.cptec.inpe.br/queimadas/risco_eta.html. Accessed on 16 June 2009

Charney JG, Quirk WJ, Chow SH, Kornfield J (1977) A comparative study of the effects of albedo change on drought in semi-arid regions. J Atmos Sci 34:1366–1385

Cook K, Vizy EK (2008) Effects of twenty-first-century climate change on the Amazon rain forest. J Climate 21(3):542–560

Costa MH, Yanagi SNM, Souza PJOP, Ribeiro A, Rocha EJP (2007) Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion. Geophys Res Lett 34:L07706

Crutzen PJ, Andreae MO (1990) Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. Science 250:1669–1678

Cruz FW, Burns SJ, Karmann I, Sharpp WD, Vuille M, Cardoso AO, Ferrari JA, Dias PLS, Viana O Jr (2005) Insolation-driven changes in atmospheric circulation over the past 116,000 years in subtropical Brazil. Nature 434:63–66. doi:10.1038/nature03365

Dirmeyer PA, Shukla J (1996) The effect on regional and global climate of expansion of the world's deserts. Q J R Meteorol Soc 122:451–482

Ehleringer JR, Cerling TE, Helliker BR (1997) C4 photosynthesis, atmospheric CO_2, and climate. Oecologia 112:285–299

Ferraz-Vicentini KR (1999) História do fogo no cerrado: uma análise palinológica. Tese de Doutorado, Universidade de Brasília

Golding N, Betts R (2008) Fire risk in Amazonia due to climate change in the HadCM3 climate model: potential interactions with deforestation. Glob Biogeochem Cycles 22:GB4007. doi:10.1029/2007GB003166
INPE (2009) Vegetation fires. http://queimadas.cptec.inpe.br. Accessed on 16 June 2009
Jungclaus JH, Keenlyside N, Botzet M, Haak H, Luo JJ, Latif M, Marotzke J, Mikolajewicz U, Roeckner E (2006) Ocean circulation and tropical variability in the coupled model ECHAM5/MPI-OM. J Climate 19:3952–3972
Justino F, Peltier RW (2008) Climate anomalies induced by the Arctic and Antarctic Oscillations: glacial maximum and present day perspectives. J Climate 21:459–475
Justino FB, Souza SS, Setzer A (2002) Relação entre focos de calor e condições meteorológicas no Brasil. Anais do XII Congresso Brasileiro de Meteorologia
Kirchoff V (1997) SCAR-B proceedings, Transec Editorial, INPE, São José dos Campos, p. 208
Nakicenovic N, Alcamo J, Davis G, De Vries B, Fenhann J, Gaffin S, Gregory K, Gr A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner HH, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, Van Rooijen S, Victor N, Dadi Z (2000) Special report on emission scenarios. Intergovernmental Panel on Climate Change
Liebmann B, Vera CS, Carvalho LMV, Camilloni IA, Hoerling MP, Allured D, Barros VR, Báez J, Bidegain M (2004) An observed trend in Central South American Precipitation. J Climate 17:4357–4367
Lin JL, Kiladis GN, Mapes BE, Weickmann KM, Sperber KR, Lin W, Wheeler MC, Schubert SD, Del Genio A, Donner LJ, Emori S, Gueremy JF, Hourdin F, Rasch PJ, Roeckner E, Scinocca JF (2006) Tropical intraseasonal variability in 14 IPCC AR4 climate models. Part I: convective signals. J Climate. doi:10.1175/JCLI3735.1
Nepstad D, Lefebvre P, Silva UL, Tomasella J, Schlesinger P, Solórzano L, Moutinho P, Ray D, Benito JG (2004) Amazon drought and its implications for forest flammability and tree growth: a basin-wide analysis. Glob Chang Biol 10:704–717. doi:10.1111/j.1529-8817.2003.00772
Oyama MD (2002) Conseqüências climáticas da mudança de vegetação no nordeste brasileiro: um estudo de modelagem. Tese de Doutorado, Instituto Nacional de Pesquisas Espaciais, São José dos Campos
Page SE, Siegert F, Rieley JO, Boehm HDV, Jaya A, Limin S (1997) The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420:61–65
Price C, Rind D (1994) Possible implications of global climate change on global lightning distributions and frequencies. J Geophys Res 99(D5)(10):823–831
Ribeiro GA, Bonfim MVR (2000) Incêndio florestal versus queima controlada. Revista Ação Ambiental 12:8–11
Salazar LF, Nobre CA, Oyama MD (2007) Climate change consequences on the biome distribution in tropical South America. Geophys Res Lett 34. doi:10.1029/2007GL029695
Saldarriaga JG, West DC (1986) Holocene fires in the Northern Amazon Basin. Quat Res 26:358–366
Salgado-Labouriau ML, Ferraz-Vicentini KR (1994) Fire in the cerrado 32,000 years ago. Current Research in the Pleistocene 11:85–87
Sanford RL, Saldarriaga JG, Clark KE, Uhl C, Herrera R (1985) Amazon rain forest fires. Science 227:553–555
Scott AC, Glasspool IJ (2006) The diversification of Paleozoic fire systems and fluctuations in atmospheric oxygen concentrations. Proc Natl Acad Sci 103:10861–10865
Sismanoglu RA, Setzer A, Justino FB, Lima WFA (2002) Avaliação inicial do desempenho do risco de fogo gerado no CPTEC. Anais do XII Congresso Brasileiro de Meteorologia, 2002
Sterl A, Severijns C, van Oldenborgh GJ, Dijkstra H, Hazeleger W, van den Broeke M, Burgers G, van den Hurk B, van Leeuwen PJ, van Velthoven P (2008) When can we expect extremely high surface temperatures? Geophys Res Lett 35:L14703. doi:10.1029/2008GL034071
Sud YC, Fennesy MJ (1982) A study of the influence of surface albedo on July circulation in semi-arid regions using the GLAS GCM. J Climatol 2:105–125
Sud YC, Fennesy MJ (1984) Influence of evaporation in semi-arid regions on the July circulation: a numerical study. J Climatol 4:383–398
Vera C, Silvestri G, Liebmann B, Gonzales P (2006) Climate change scenarios for seasonal precipitation in South America from IPCC-AR4 models. Geophys Res Lett 33(13). doi:10.1029/2006GL025759
Xue Y, Shukla J (1996) The influence of land surface properties on Sahel climate. Part II: aforestation. J Climate 9:3260–3275
Xue Y, Shukla J (1993) The influence of land surface properties on Sahel climate. Part I: desertification. J Climate 6:2232–2245