Spatio-temporal variability of burned area over Brazil for the period 2005-2010 using MODIS data

Renata Libonati [1,2]
Carlos DaCamara [3]
Alberto W. Setzer [2]
Fabiano Morelli[2]

[1] Universidade Federal do Rio de Janeiro - UFRJ
CEP 13416-000 – Rio de Janeiro - RJ, Brasil
renata.libonati@igeo.ufrj.br
[2] Instituto Nacional de Pesquisas Espaciais - INPE
Caixa Postal 515 - 12245-970 - São José dos Campos - SP, Brasil
{alberto.setzer, fabiano.morelli}@cptec.inpe.br
[3] Instituto Dom Luiz – IDL/FCUL
Lisboa - Portugal
cdcamara@fc.ul.pt

Abstract. Brazil contributes as a source of greenhouse gases, aerosols and trace gases to the atmosphere, in particular, due to the continuous conversion of vegetation to pasture and agriculture land using fire practices. Although the Brazil presents huge numbers of fire events, there is a lack of studies in order to analyze the agreement among currently available burned area products, both in terms of extent and location of the areas burnt over this region. This issue is of particular interest since the accuracy of burned area maps is related to the uncertainties in the quantification of atmospheric biomass burning emissions. Accordingly, we present and analyze the results of three currently burned area (BA) products derived from MODIS data, namely AQM (INPE), MCD45A1 (NASA) and MCD64A1 (NASA). The procedure is applied to quantify the overall temporal and spatial distribution patterns of burned areas in Brazil for the period 2005 – 2010 and obtained patterns are compared for each Brazilian biome and related to the respective patterns of fire pixels derived from remote sensing. Results show there is a reasonable spatial agreement in the location of burned areas among the three products. However, there is a major disagreement in area extent. The AQM product presents substantially higher estimates of BA than the NASA products, being on average 5.8 and 4.4 times larger than MCD64A1 and MCD45A1, respectively. In general, AQM presents values much close to active fires than the NASA/MODIS BA products.

Keywords: Burned area, MODIS, Remote Sensing.

1. Introduction

Fires induces modifications in 8 of the 13 radiative forcing terms and has a considerable positive feedback on the climate system (Bowman et al., 2009). Biomass burning from vegetation fires is a major source of greenhouse gases, aerosols and trace gases to the atmosphere (including black and organic carbon) (Dentener et al., 2006, Zhang et al., 2008, van Leeuwen et al., 2010). The radiative budget and cloud microphysics are also disturbed by the release of smoke aerosols from biomass burning (Andrea et al., 2004,). In addition, vegetation fires are one of the most important causes of land use/cover dynamics (Lambin and Geist, 2006), destroying and altering vegetation structure and depositing charcoal and ash on the surface, which have an important impact on surface albedo (Sellers et al., 1996; Jin and Roy, 2005). Therefore the importance of understanding spatial and temporal fire patterns increases as a function of the actual recognition of anthropogenic influences on Earth climate. Additionally, information about the extent, location and time of burned areas reveals useful to assess the economic value of the damage area, an issue that is becoming more and more relevant nowadays.

Currently, due to the very broad spatial extent and the limited accessibility of some of the largest areas affected by fire, the instruments on-board satellites are the only available operational systems capable to collect cost-effective burned area data at spatial and temporal resolutions appropriate to most modeling applications (Pereira, 1999). Over the last years, special attention has been devoted to mapping burned areas using remote sensing at global scale, covering a variety of techniques based on different spatial, spectral and temporal resolutions. These initiatives include, the 1-km L3JRC product (Tansey et al., 2008), covering the period of April 2000 to March 2007, and produced from SPOT VEGETATION data, and the 1-km GLOBCARBON burned area product, spanning April 1998–December 2007, derived from SPOT VEGETATION, Along-Track Scanning Radiometer (ATSR-2), and Advanced ATSR (AATSR) imagery using a combination of mapping algorithms (Plummer et al., 2006). At a finer resolution (500 m), appears the Moderate Resolution Imaging Spectroradiometer (MODIS) burned area products by NASA, the so called MCD45 (Roy et al., 2008) and MCD64A1 (Giglio et al., 2009). Finally, it is worth mentioning the Global Fire Emissions Database (GEFD) initiative that consist in monthly burned area estimates aggregated to 0.5 spatial resolution for the time period July 1996 through mid-2009 using four satellite data sets (Giglio et al., 2010).

It is well recognized that those global scale burned area maps are essential for a variety of application, in particular for global estimation of greenhouse gases, aerosols and trace gases emissions to the atmosphere. Nevertheless, accordingly to several authors (Boschetti et al., 2002, Giglio et al., 2009, 2010) large disagreements in the quantification of biomass burning remain among these products, both in terms of annual extent of the areas burnt and in terms of location of those areas. In fact, an accurate global algorithm to detect surface changes caused by fire is still hampered by the complexity, diversity and huge number of biomes involved.

The above mentioned limitations of burned area estimations at global scales suggest the development of regional algorithms which take into account local characteristics such as vegetation type, soil and climate. Accordingly, since 2013 INPE has developed a monthly burned area product (AQM-INPE) for Brazil based on information from MODIS 1km images (Libonati et al., submitted). The product relies on an algorithm that was specifically designed for ecosystems in Brazil, taking advantage of the ability of MIR reflectances to discriminate burned areas (Libonati et al., 2011)

The main objective of this work it to present and analyze the results of three currently available burned area products derived from MODIS data over Brazil, namely AQM (INPE), MCD45A1 (NASA) and MCD64A1 (NASA). The procedure shows the overall temporal and spatial distribution patterns of burned areas in Brazil for the period 2005 – 2010 for the three products. Obtained patterns are compared for each Brazilian biome and related to the respective patterns of fire pixels derived from remote sensing.

2. Data

2.1 INPE/MODIS burned area data

We use here the AQM/INPE burned area product from 2005-2010. The AQM/INPE burned area is based on an automated regional algorithm using information from MODIS imagery at 1km resolution over Brazil. The algorithm relies on the so-called W burning index that is defined in a transformed NIR-MIR space. The AQM approach is currently in pre-operational phase at INPE and additional tuning experiments are currently being carried on. The operational dissemination of monthly BA is expected to start until the end of 2014. The AQM algorithm is also being applied to MODIS data since 2000 year until the present with the aim of building up a long-term database of BA for Brazil.

2.2 NASA/MODIS burned area data

We use here MODIS BA official products namely the MCD45A1 Burned Area Product (Roy et al., 2005) and MCD64A1 Direct Broadcast Monthly Burned Area Product (Giglio et al., 2006). They were freely downloaded from the University of Maryland ftp sites (ftp://user@ba1.geog.umd.edu and ftp://fuoco.geog.umd.edu/db/MCD64A1/. Tiles for the two BA products over Brazil between 2005 and 2010 were then mosaicked and remapped using the Modis Reprojection Tool.

MCD45A1 is a monthly Level 3 gridded 500 m product containing per-pixel burning and quality information, and tile-level metadata. Quality information is given using five confidence levels of detection from 1 (most confident) down to 4 (least confident). Confidence level 5 denotes detections over agricultural areas. The MCD45A1 data used in our analysis include quality assurance flags from 1 to 4. MCD64A1 is globally available on a monthly basis back to August 2000 at 500m resolution. The MCD64A1 product is currently used in the framework of the Global Fire Emissions Database (GFED) initiative and will replace MCD45A1 in the upcoming MODIS Collection 6. Among the five data layers from MCD64A1, only the Burn Date was used in our study, as this product does not have flags containing confidence levels.

2.3 Active fires

Information about active fires was based on data provided by GOES, NOAA, MSG-2, TRMM, ATSR, AQUA and TERRA satellites were obtained from INPE active fire database (details are available at http://www.dpi.inpe.br/proarco/bdqueimadas/).

2.4 Biome classification over Brazil

The territory of Brazil was subdivided into different regions following the biome classification developed by Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA). The IBAMA classification includes six main biomes covering similar climatic and biological conditions; Cerrado, Amazônia, Caatinga, Pantanal, Mata Atlântica and Pampa (Figure 1).

Figure 1. The six main biomes of Brazil according to the IBAMA classification.

3. Results and Discussion

3.1 AQM/INPE results

Monthly values of BA over Brazil (x 10^3 km2) as obtained from AQM for the period 2005-2010 are shown in Table 1. The mean annual amount of burned area is 800 x 103 km2 which corresponds to about 10% of the territory of Brazil. The highest monthly mean amount is observed in September, followed by October whereas March presents the lowest amount followed by the month of February. The most severe year is 2007, the total amount of slightly more than 1200 x 103 km2 corresponding to about 14% of the Brazilian territory. The year of

2007 is followed by 2005 and 2010, while 2006 and 2009 are the years with less area burned in Brazil, followed by 2008. The spatial patterns of BA on a yearly basis are presented in Figure 2 and the intensity of burned areas is especially worth noting along the Arc of Deforestation, where the agriculture boundary progresses in direction of the forest.

Table 1. Monthly values of BA over Brazil (x 10^3 km^2) as obtained from AQM for the period 2005-2010. Monthly mean values are presented in the last column whereas total yearly amounts are given in the last row.

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**Mean**
Jan	4.0	5.0	27.3	7.4	14.0	3.5	9.5
Feb	2.4	10.7	9.4	5.9	6.2	6.0	6.7
Mar	4.2	4.8	5.6	4.0	9.6	2.8	5.1
Apr	7.1	5.3	5.7	4.7	10.5	10.4	7.2
May	21.9	13.6	15.2	8.5	23.2	3.7	14.3
Jun	58.2	39.6	56.6	24.8	27.2	7.3	35.6
Jul	61.0	70.6	94.4	49.5	61.8	148.3	80.9
Aug	163.0	136.1	170.4	80.2	80.4	181.0	135.2
Sep	183.3	167.6	347.3	157.6	143.1	189.5	198.0
Oct	284.9	63.2	239.3	179.0	82.7	197.5	174.4
Nov	109.9	39.6	216.9	97.8	61.9	62.2	98.0
Dec	36.3	16.6	32.3	56.8	59.6	9.3	35.1
Total	**936.2**	**572.7**	**1220.4**	**676.2**	**580.2**	**821.5**	**800.5**

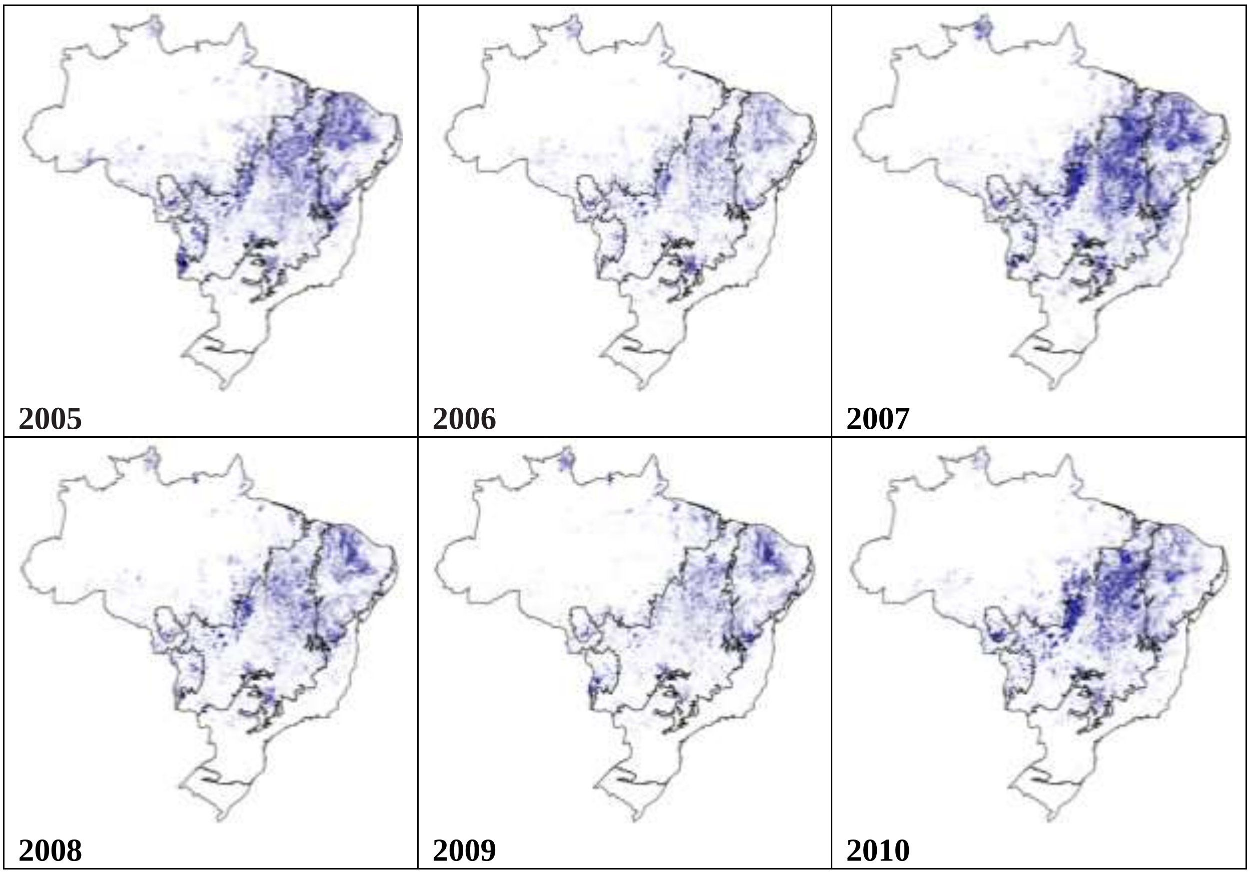

Figure 2. Spatial patterns of burned area over Brazil for the 6-year period: 2005 (top-left panel), 2006 (top-central panel), 2007 (top-right panel), 2008 (low-left panel), 2009 (low-

central panel) and 2010 (low-right panel). Black lines delimit the six biomes as shown in Figure 1.

The biomes present different characteristic both in terms of annual amounts and annual cycles of BA (Figure 3). The Cerrado biome is the one with largest annual mean of BA (410 x 10^3 km2), followed by Caatinga (194 x 10^3 km2) and Amazônia (107 x 10^3 km2). The Amazônia biome has two annual peaks of BA, the largest one between August and October and the secondary one in February. The Cerrado shows a marked annual peak which occurs during the dry season from July to October. The Caatinga has one peak from November to January, while Pantanal and Pampa show two annual peaks around May and September. The Mata Atlântica does not show a markedly defined peak of BA, but a slight peak may be identified during the winter months.

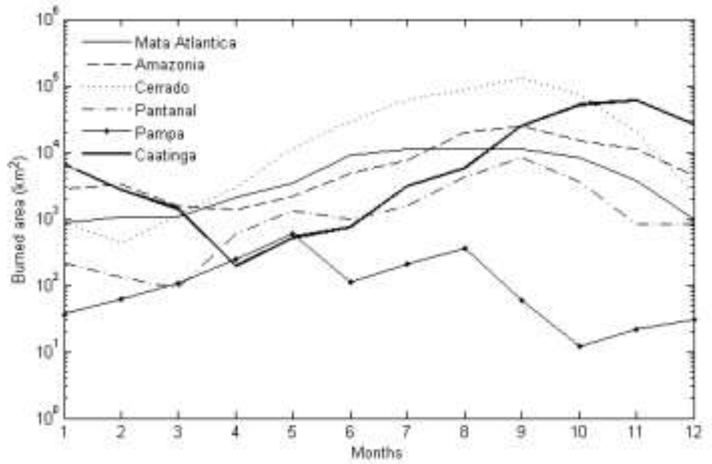

Figure 3. Mean annual cycles (2005-2010) of BA for the six main biomes of Brazil.

3.2 Comparison of the three BA products and active fires

Table 2 shows total yearly amounts of BA (x 10^3 km^2) in Brazil for 2005-2010 as derived from AQM, MCD64A1 and MCD45A1. While all three BA products show similar temporal behavior, there are significant differences regarding the magnitude of the amount of burned area totals. The AQM product presents substantially higher estimates of BA than the NASA products, being on average 5.8 and 4.4 times larger than MCD64A1 and MCD45A1, respectively. The higher discrepancies between AQM and NASA products appear associated to years with low burned area like 2006, 2008 and especially in 2009.

Table 2. Total yearly amounts of BA (x 10^3 km^2) in Brazil for 2005-2010 as derived from AQM, MCD64A1 and MCD45A1. The last column provides the annual mean values for each product.

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**Mean**
AQM	936.2	572.7	1220.4	676.2	580.2	821.5	800.5
MCD64A1	142.3	61.9	258.7	73.0	30.8	250.8	136.7
MCD45A1	150.0	71.0	360.0	112.1	34.2	364.4	181.9

Table 3 presents the comparison between the percentages of the total area of Brazil that has burned in the period accordingly to each BA product compared with the active fire information. Here, we have considered an approximation that each active fire corresponds to 1 km^2 of burned area, although there is no guarantee that BA and active fire are proportional in such way. Anyway, the results of Table 3 show that AQM presents values much close to active fires than the NASA/MODIS BA products. The study from Roy et al (2008) have shown an under detection of MCD45 relative to the active fire product in forested regions of Brazil. From July 2001 to June 2002 the BA product reports considerably fewer detections than the active fire product in South America, with 1.72×10^5 km^2 versus $3.79\times10^5 km^2$, respectively.

Table 3. Percentage of the total area of Brazil that has burned in the period accordingly to each BA product compared with active fire information. The last line depicts annual mean values (% per year).

	AQM	**MCD64A1**	**MCD45A1**	**Active fire**
2005	10.8	1.7	1.8	8.7
2006	6.6	0.7	0.8	5.5
2007	14.2	3.0	4.2	9.0
2008	7.8	0.9	1.3	5.8
2009	6.7	0.4	0.4	4.3
2010	9.5	2.9	4.3	8.9
Mean	9.33	2.88	3.85	7.05

Validation of results from the three products over Brazil is a very difficult task since until now there is no official BA database covering the entire country. Data about location, area burned and time of fire occurrence are available for a small number of limited areas and the information is generally organized by different working groups, with a variety of techniques (in situ measurements, remote sensing techniques), diverse classification approaches (supervised or unsupervised classifications, visual inspection, etc.) and distinct temporal and spatial resolutions; besides, most of these initiatives are sporadic and none of them is considered official.

Burned area comparison with active fires has been used as a way to circumvent these difficulties (Roy et al 2008) but such an approach is not straightforward due to large discrepancies between the two parameters. However, as discussed at the end of the previous section, this type of comparison provides useful information about the performance the BA product in areas where no other reference data are available.

The territory of Brazil was therefore subdivided into grid cells of 50x50 km; for each grid cell, values of BA as estimated by AQM, MCD64A1 and MCD45A1 were correlated with corresponding number of cells where at least one hot spot was detected. As shown in Table 4, values of the correlation coefficient (r_h) were computed for each biome of Brazil on a yearly basis covering the period 2005-2010; the Pampa biome was not included because of the small size of the sample. For each year and biome the highest value of r_h is indicated in bold and it may be noted that the AQM product presents substantially higher values than the two NASA products for the large majority of years and biomes. The exceptions are 2005 for Pantanal and 2010 for all biomes but Caatinga but differences from values of r_h for AQM to leading values are not larger than 0.02 (except for Mata Atlântica in 2010 where the difference is 0.1).

Finally it is worth noting that in the case of the AQM product the Amazônia biome presents values of r_h that are substantially lower than the remaining ones. This may be due to obscuration of BA by overstory vegetation; although the radiative signal by understory active fires is strong enough their identification, that is not the case for associated burned areas since understory fires, which burn the floor of standing forests, do not completely remove the forest canopy (Nepstad et al. 1999). Understory fires are one of the most important types of forest impoverishment in the Amazon Alencar et al. (2006), but, as pointed out by Roy et al. (2008) active fire observations may be more successful in capturing fire activity in tropical high tree cover regions than BA datasets.

Table 4. Correlation coefficients between BA from AQM, MCD64A1 and MCD45A1 computed in grid cells of 50x50 km and number of pixels where active fire was detected, for five biomes over Brazil and for the period from 2005-2010.

		2005	**2006**	**2007**	**2008**	**2009**	**2010**
Cerrado	**AQM**	**0.82**	**0.76**	**0.89**	**0.72**	**0.71**	0.83
	MCD64A1	0.63	0.52	0.79	0.49	0.42	**0.85**
	MCD45A1	0.62	0.59	0.78	0.43	0.42	**0.85**
Amazônia	**AQM**	**0.63**	**0.57**	**0.71**	**0.54**	**0.48**	0.73
	MCD64A1	0.62	0.47	0.67	0.36	0.16	**0.75**
	MCD45A1	0.41	0.32	0.62	0.28	0.11	0.71
Caatinga	**AQM**	**0.83**	**0.70**	**0.80**	**0.76**	**0.85**	**0.75**
	MCD64A1	0.32	0.19	0.47	0.35	0.18	0.60
	MCD45A1	0.30	0.17	0.43	0.39	0.18	0.60
Pantanal	**AQM**	0.86	**0.73**	**0.86**	**0.76**	**0.90**	0.69
	MCD64A1	**0.87**	0.67	0.65	0.53	0.72	0.70
	MCD45A1	0.85	0.54	0.85	0.56	0.75	**0.72**
M.Atlântica	**AQM**	0.79	0.68	0.75	0.71	0.72	0.61
	MCD64A1	0.41	0.60	0.66	0.45	0.52	**0.71**
	MCD45A1	0.28	0.38	0.38	0.25	0.25	0.44

4. Conclusions

We have presented and analyzed the results of three currently burned area products derived from MODIS data, namely AQM (INPE), MCD45A1 (NASA) and MCD64A1 (NASA). The procedure is applied to quantify the overall temporal and spatial distribution patterns of burned areas in Brazil for the period 2005 – 2010 and obtained patterns are compared for each Brazilian biome and related to the respective patterns of fire pixels derived from remote sensing.

According to the AQM results a mean of 800 x 10^3 km^2/year has burned over the Brazil during the period from 2005-2010 (which accounts for 10% of the territory per year). The most severe year is 2007, followed by 2005 and 2010; 2006 and 2009 are the years with less area burned, followed by 2008. The Cerrado biome is the one with the largest BA, followed by Caatinga and Amazônia.

Estimates of BA over Brazil from AQM, MCD45 and MCD64 products for the period present a similar inter-annual variability. There are however marked differences among the magnitude of the estimates of total BA. On average, MCD64A1 and MCD45A1 provide estimates that are about 5 times smaller than AQM. In general, AQM presents values much close to active fires than the NASA/MODIS BA products

For the very large majority of years and biomes, the AQM product presents values of correlation with active fires much higher than the NASA BA products. These results are in agreement with Roy et al (2008), who have pointed out an under detection of BA by the MCD45 product relative to the active fire product in forested regions of Brazil.

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