Answer to the Editor:
"A novel methodology using MODIS and CERES for assessing the daily radiative forcing of smoke aerosols in large scale over the Amazonia"
by E. T. Sena and P. Artaxo submitted to Atmos. Chem. Phys.

We would like to thank the editor for his time and for his support handling the manuscript. We would also like to thank both reviewers for their helpful suggestions on how to improve the revised manuscript. All the reviewers’ comments were addressed and the manuscript was modified according to their suggestions. Please find attached a point-by- point response to both referees’ comments specifying the changes in the revised manuscript, as well as a marked-up manuscript version, showing all the corrections implemented.

Interactive comment on "A novel methodology using MODIS and CERES for assessing the daily radiative forcing of smoke aerosols in large scale over the Amazonia"

by E. T. Sena and P. Artaxo submitted to Atmos. Chem. Phys.

Answers to Anonymous Referee #1:

We would like to thank referee #1 for the very careful review. We have really appreciated the several suggestions and comments that helped us improving the revised manuscript. In bold type, the issues raised by the reviewer, followed for our action in each issue raised.

This paper describes a new methodology to measure the direct aerosol radiative forcing (DARF) at the top of the atmosphere. For this purpose, the authors used the MODIS and CERES satellite instruments during the biomass burning season over the Amazonian region. They compare their DARF results with other studies using a different methodology and with ground-based stations. The structure of the paper is good and we clearly see where the authors go. Results are reasonably well presented and I recommend the paper for publication in ACP after the authors address the following comments.

General comments:

1) The abstract is not concise enough. In particular, I would summarize more the 2nd and 3rd paragraph. I am not sure that you need to detail your methodology here (MODIS clean scenes, etc...). I also dont think that correlation equations need to be written. It makes the abstract heavy. I would remove them and slightly modify your last sentences such as "We showed that our methodology agrees well with other satellite remote sensing studies, ground-based measurements and radiative transfer models..."

We completely agree with the reviewer comments. The abstract was too detailed. We've changed the abstract in the revised version according to the reviewer's suggestions.

2) I have concerns about your explanations attributing the 24h-DARF daily variation that you show in Figure 2 and 3, reported in Section 3.

Page 31524

Line 15-17: You attribute the difference of 24h-DARF between 2 days (13th and 15th of August) to the transport and atmospheric circulation.

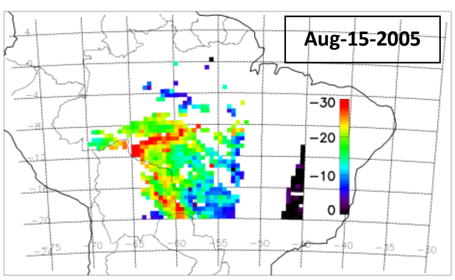
Page 31525

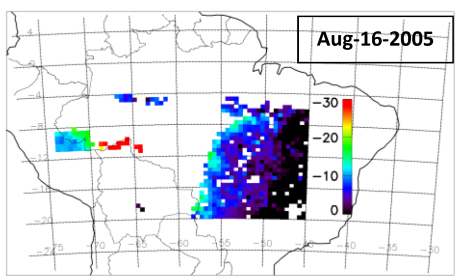
Line 8-9: You attribute the 24h-DARF daily variation to the change in cloud cover.

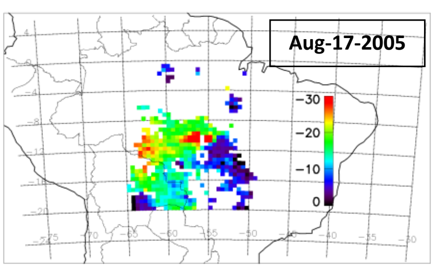
Where do you see that these variations are due to the transport, atmospheric circulation or cloud cover? I would like to see a plot of the daily cloud cover area in your region for each day (I think MODIS retrieves this product). Are these clouds over burning areas which could decrease 24h-DARF ? In addition, did you look at aerosol emissions for these days (e.g., with a satellite fire product or with a biomass burning inventory (e.g., GFED)) ? On Figure 3, the 24h-DARF shows lower values for 2007 (down to -25 W.m-2) than for 2005 (-20 W.m-2) and 2006 (-15 W.m-2). A quick look at the GFEDv3 inventory seems to be consistent with those results since it shows larger biomass burning emissions in 2007 than in 2005 and 2006. What about 2008, 2009 ? It would be easier to compare different years if you could plot data on the same plot. Maybe different color lines for each year with a 3 days smooth? There are also several papers in the litterature refering to the transport of aerosols in the Amazonian region that could help.

This is a long question, and to answer it fully, we will divide the answer in several topics:

<u>On cloud fraction and CERES and MODIS coverage</u>: Thanks for raising this question. We agree that this point was not clear in the manuscript. Actually, the variation on daily DARF from one day to the next is not caused only by changes in fire locations, transport and cloud coverage. The daily DARF variation is also influenced by differences in the satellite imaged area. Since the Terra satellite track changes from one day to the other, the area scanned by CERES-MODIS one day is not exactly the same as the area scanned on the next day. Due to its polar orbiting track, every day the scanned area changes slightly, finally repeating itself after about 16 days. The figure below shows two examples of the 24h-DARF for Aug-15-2005 (top, left), Aug-16-2005 (top, right) and Aug-17-2005 (bottom).

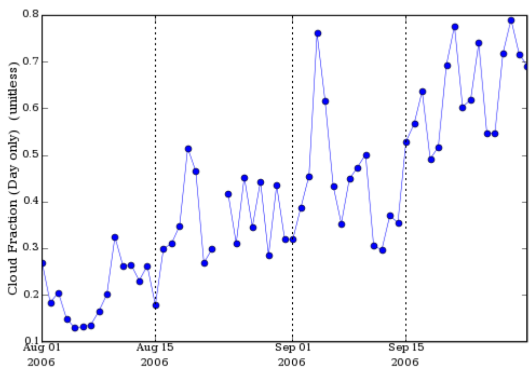






We can observe in these two pictures the effect of the changing track area. The mean 24h-DARF on Aug-16 is smaller than the 24h-DARF on Aug-15 and Aug-17. This is due to the fact that CERES and MODIS didn't cover the area that was the most impacted by biomass burning aerosols on Aug-16. This section of the manuscript was fully reformulated discussing this effect in details. This feature of the technique is discussed in more details now in the revised manuscript.

The next picture shows an example of the mean daily cloud cover for each day at the study area in 2006. We can observe that changes in cloud cover during the biomass burning season also influence DARF retrievals.



On atmospheric circulation and aerosol transport: During the development of this work, we have analyzed fire products from MODIS and also GOES over the Amazonia during the biomass burning season. The aerosol distribution and RF results presented in this manuscript is consistent with fire maps as well as with AERONET AOD measured at several sites. Several papers discuss biomass burning transport over the Amazonia and were already cited in the manuscript, such as Freitas et al., 2005, Longo et al., 2009 and Andreae et al., 2001. A brand new paper by Mishra et al., 2015, in press in Atmospheric Environment discusses in detail the issue of the correlation between smoke and fire in Amazonia. This paper was now also cited in the revised manuscript as well as some others. We also enhanced the discussion addressing the points the reviewer raised on fire counts and atmospheric transport.

On enhancing Figure 3: We really thank the reviewer and we've accepted the suggestions on enhancing Figure 3 that shows the forcing on a day by day basis during dry season. We modified this figure on the revised manuscript to include all the years analyzed in this work, as suggested. We've tried to put all data in only one plot, but as there were 9 years of data, we found that the plot became very crowded and a bit confusing. So, we decided to include several sequential plots for all years, using the same scale for DARF24h. We also expanded the discussion on the daily variability of the DARF on the manuscript to include all years of data and emphasize the interannual variation of the DARF24h.

3) I would remove the Figure 4. This figure comes from another paper which is cited and it doesnt add anything to your paper. We understand the difference between your approach and that used in previous studies. Your explanations on page 31525 are enough. Maybe same for Figure 6.

We agree that Figure 4 does not add critical information on the paper. We removed it. As for figure 6, we think that it is important in our discussion, so we prefer to keep it in the manuscript.

4) I agree with you when you say that a small SSA variation induces a large 24h-DARF variation for large AOD values (e.g., AOD=5). However, you showed that the mean AOD over Amazonia is about 0.2 to 0.4 during dry seasons. So, it would be more judicious to tell us about the difference in 24h-DARF at these AOD for different SSA. Are those 24h-DARF variations at these low AOD values (0.2-0.4) in range of variations that you observe with AERONET ? You might need to change the x-axis range on Figure 10 as well (e.g., from 0 to 1 or 0 to 2).

Thanks for pointing that out. A variation of 0.03 on SSA for the mean AOD observed over the Amazonia (0.2 to 0.4) would affect the 24h-DARF in about 1 to 2 W/m^2. To evaluate if these values are consistent with the 24h-DARF variation observed with AERONET, the database was divided in AOD bins of 0.05 and the standard deviation of AERONET’s 24h-DARF on each bin was analyzed. This analysis showed that for AOD varying from 0.2 to 0.4, the standard deviation of the AERONET 's 24h-DARF on each bin varied between 1.5 and 2.7 W/m^2. This variation is higher than the one obtained using SBDART, because in those simulations, only single scattering albedo was varied and other aerosol and atmospheric properties were fixed. However, there are other variables that influence the 24h-DARF observed by AERONET besides single scattering albedo, such as scattering phase function, size distribution and atmospheric water vapor content. This discussion was included in the revised version of the manuscript. The x-axis range on Figure 10 was also modified, and now ranges from 0 to 2, as suggested.

5) I found the English approximative and heavy but the paper is understandable. Here after, I listed some specific comments but there is space for more improvements.

We've really appreciated the referee's helpful suggestions on improving the overall language of the manuscript. We've followed all the referee's specific comments on correcting the English and we've also reviewed the language over the entire manuscript.

Specific comments:

When several references are mentioned, put them in chronological order please.

In the revised version of the manuscript the citations were put in chronological order.

Page 31516

1) Line 3: Remove "For that,"

Done.

2) Line 8: Replace studies by study

Done.

3) Line 20: ...in the estimate of...

Done.

Page 31517

4) Line 24: Remove "important"

Done.

Page 31518

5) Line 6-9: Rephrase sentence

The sentence was rephrased to: "This strong increase in aerosol concentration is accompanied by a significant modification in particle size distribution, since most of the particles emitted during burning events belong to the fine mode".

6) Line 13-14: Remove "and other properties"

Done.

7) Line 23-24: ...with ground-based remote sensing measurements (ref) or in-site field-campaigns

(ref)

Done.

Page 31519

8) Line 11: ...is estimated to be about...

Done.

Page 31520

9) Line 5: Remove "retrievals"

Done.

10) Line 7: These both instruments...

Done.

11) Line 16: MODIS measures...

Done.

12) Line 19: ...about cloud and aerosol optical...

Done.

13) Line 25: ...aerosol and cloud properties...

Done.

Page 31521

14) Line 2: ...shortwave flux retrievals at the TOA from Terra satellite...

Done.

15) Line 12-13: ...measured in background (Fcl) and polluted (Fpol) conditions.

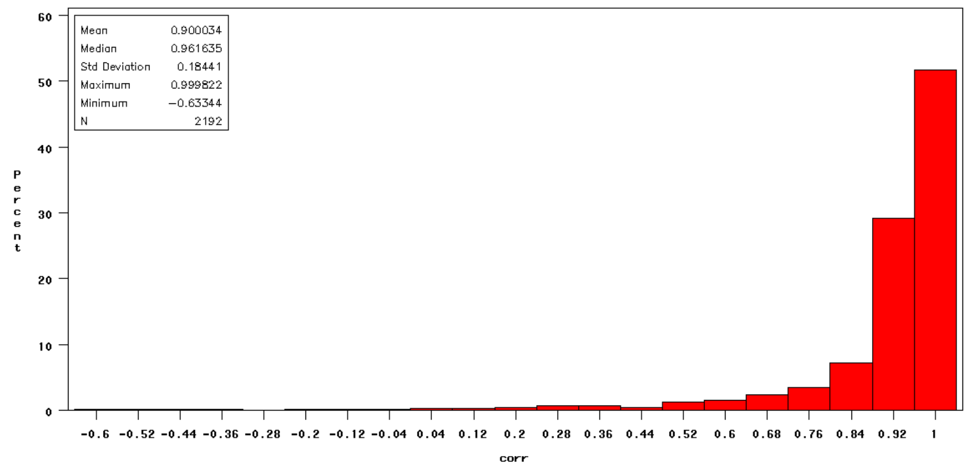
Done.

16) Line 19: Can you explain why you take 0.1 as the threshold for background scenes ? Does it come from another paper ?

To define the AOD threshold for background conditions, we've analyzed AERONET's AOD during the wet season. After checking AERONET data, the threshold of AOD < 0.1 seemed to be an appropriate choice for non-polluted conditions. This discussion was included in the final manuscript.

17) Line 22: Is the example showed in Figure 1, a best case scenario or it is representative of each grid cell ? Why did you choose to show this example more than another ?

That's an interesting question. The example showed in figure 1 is not a best case scenario. If we check the distribution of the correlation between Fcl and cos(SZA), we can see that for about 80% of the cases the correlation is larger than 0.90, as shown in the figure below. These results point out another advantage of applying this new methodology to evaluate the DARF. This point was now emphasized in the revised manuscript.



18) Line 25: "approximation"

Done.

Page 31522

19) Line 13: Remove "of the"

Done.

20) Line 16: CERES radiance measurements

Done.

Page 31523

21) Line 1: Remove "For this,"

Done.

Page 31524

22) Line 9: ...from about -30 to -15

Done.

23) Line 13: ...from -30 to -15

Done.

Page 31525

24) Line 6: Remove "That is"

Done.

25) Line 6-7: Replace more negative by decrease and less negative by increase

Done.

26) Line 8: ...from one day to another...

Done.

27) Line 13-14: ...was calculated by using...

Done.

28) Line 22: Replace "that is, in a" by "with a"

Done.

Page 31526

29) Line 5-7: ...is always lower than...for this 10 year period (2000 to 2009) is -8.2...is -5.2...

Done.

30) Line 16: Replace less negative by larger

Done.

31) Line 22: Replace most certainly by very likely

Done.

32) Line 23: Remove "that was"

Done.

33) Line 26: ...between aerosol optical depths obtained by these two collections is due to the fact...

Done.

Page 31527

34) Line 18-19: correlation

Done.

35) Line 19: ...to 2009 is -0.86+-0.03 which is better than the mean...

Done.

36) Line 24: ...TOA flux estimates...

Done.

37) Line 26: Replace rely by relies

Done.

38) Line 27: ...those flux retrievals.

Done.

Page 31528

39) Line 4: ...in the calculated DARF...

Done.

40) Line 6: ...that accounts for...

Done.

41) Line 23: ...to retrieve AOD and...

Done.

Page 31529

42) Line 23: with 1 within 2 uncertainties ??? I dont understand what you mean here

Thanks. I did not express myself clearly. We rephrased the text to show that the agreement between DARF AERONET and DARF CERES is acceptable within the standard deviations.

43) Line 26-27: AERONET sunphotometers are at the surface and CERES-MODIS instruments are at 705 km aboard...

Done.

Page 31530

44) Line 10-11: In order to properly do that we compare CERES-MODIS data at the TOA with...

Done.

Page 31531

45) Line 4: ...are compatible with 1 and 0, respectively, within one uncetainty ??? Same as before, I dont understand.

Once again, I did not express myself clearly. We rephrased the text to show that the agreement between the BOA Flux from pyranometers and SBDART is acceptable within the standard deviations.

46) Line 9: ...pyronanometer measurements.

Done.

47) Line 16: To me, a slope of 0.86 is not close to y=x. A difference of 14% is not negligeable.

That's true. This sentence was removed from the revised manuscript. The text has been changed in order to further emphasize the sources of uncertainty (surface albedo model, aerosol single-scattering albedo, aerosol phase function, etc.) in radiative transfer DARF that contribute to this difference. Nevertheless, we also emphasize that given all those potential sources of uncertainty the comparison between space-based assessments of the DARF and radiative transfer evaluations of the DARF, using ground-based aerosol measurements a slope of 0.86±0.06 is still a very good result.

Page 31532

48) Line 8: ...significant and it shows that aerosol single scattering albedo is a critical parameter to

assess DARF.

Done.

49) Line 13: consists

Done.

Page 31533

50) Line 10: ...methodology is applied.

Done.

51) Line 12: Reformulate the sentence: The intercomparison between...

The sentence was reformulated to: "The DARF evaluated using the new methodology proposed in this work was compared with AERONET and SBDART DARF assessments. The results obtained from those DARF intercomparisons were very satisfactory."

52) Line 23: ...resulting in a better correlation between...

Done.

Figure 2: caption, distributions

Done.

Figure 5: What happened in 2004. Can you mention it ?

The year 2004 presents a high amount of MOD04 missing values for aerosol and cloud properties in CERES-SSF database. The percentage of missing MOD04 cloud and aerosol properties was around 45% for 2004, while for all the other years (2000-2003 and 2005-2009) missing values were on average only 10%. CERES science team has been formally contacted and informed about this problem and they are working on understanding it. They expect that this problem won't show up in CERES-SSF Edition 4, which is now being processed and will use MODIS collection 5 for all years, including 2004. In the revised manuscript, we included more information about this problem in Sections 3.2 and 3.3.

Interactive comment on "A novel methodology using MODIS and CERES for assessing the daily radiative forcing of smoke aerosols in large scale over the Amazonia"
by E. T. Sena and P. Artaxo submitted to Atmos. Chem. Phys.

Answers to Anonymous Referee #2:

We would like to thank referee #2 for the very careful review. We had really appreciated the several suggestions and comments that helped us improving the final manuscript. In bold type, the issues raised by the reviewer, followed for our detailed action in each issue raised.

The manuscript introduced a novel method for defining smoke aerosol radiative forcing over Amazonia using satellite data. The key improvement in this method is that the aerosol forcing can be defined on a daily basis. In addition, the satellite-based results compare well with the AERONET inversions, which is promising. I recommend the publication of this article after some revision of the current version of the manuscript. One of the major issues relates to the terminology and the exact definitions of the key parameters (e.g. aerosol forcing, clear vs. aerosol-free environment). The authors should be more clear in which kind of satellite-based studies their method could improve the temporal resolution, and also discuss a bit about the limitations of this method. From this current version of the manuscript the reader might get the impression that this specific method could be used to improve all the previous studies where coincident CERES and MODIS satellite observations were used to estimate the direct aerosol radiative effect (forcing), which, to my understanding, is not true.

General comments:

1) The abstract is too long and in some parts too detailed. The authors should rewrite the abstract in a more concise way, focusing on the key findings.

We fully agree with the reviewer comments. The abstract was rewritten in a more concise way, as suggested.

2) The authors should define more clearly already in the introduction what they mean by DARF, i.e. that it considers the direct aerosol radiative forcing of smoke aerosols only. Also, they should be more specific when discussing about ”previous studies” that also used coincident CERES and MODIS observations to define the direct aerosol radiative forcing (/effect), especially whether those studies considered the radiative forcing of all aerosols or only of some specific aerosol type. The difference is that in this kind of specific forcing study both polluted (smoke) and background (clean) (AOD<0.1) SW TOA fluxes can be observed. On the other hand, when considering the total aerosol forcing, the aerosol-free flux (i.e. AOD=0) can not be observed. Therefore, at least in some of the ”previous studies” referred in the current manuscript, coincident AOD- TOA flux observations over longer time period (months) were needed in order to get an estimate for the mean aerosol-free flux, which also set the boudaries to

the temporal resolution in which the total aerosol radiative forcing could be defined. I.e. if understood correctly, your method can be used to define F_clean – F_pollution at high temporal resolution but not F_aerosol-free – F_all aerosol. For example in Sect. 3.3 authors could emphasize already earlier in the section that in the "previous studies", i.e. Patadia 2008 and Sena et al. 2013, the aim for using coincident AOD-TOA flux satellite observations was to find the mean TOA flux for aerosol-free conditions (AOD=0) but in this study the "clean" environment is defined as AOD<0.1. I.e the "previous studies" actually defined the total aerosol forcing. In the case of Amazonia the total aerosol forcing is most probably nearly the same as smoke aerosol forcing, but generalizations to other kind of environments do not necessarily work similar way.

We've really appreciated the referee's suggestions on how to improve the introduction and clarify the differences between the methodology introduced in this work and previous studies. Both, the introduction and section 3.3, were modified in the revised manuscript in order to explain the differences between the total DARF and smoke DARF. However, as aerosol-free conditions (AOD=0) don't exist, considering a more realistic clean condition (that is, defining Fclean in the presence of background aerosols) could be regarded as an improvement over previous methodologies. Since background aerosols are always present in the atmosphere, the contribution of background aerosols to the radiative balance should not be considered as forcing in the strict sense. In fact, as pointed out above by the referee, some authors define the contribution of background + polluted aerosols as the direct radiative effect instead of direct radiative forcing (eg., Yu et al., 2006).

3) The water vapour content variation had been taken into account in the radiative transfer simulations but how large effect these variations could have when defining the instantaneous satellite-based forcing?

That is an interesting and relevant question. CERES does not take into account water vapor variations to define its angular distribution models (ADMs), used to convert radiances to flux. Since CERES ADMs are defined based on monthly averages, there could be a bias at the flux at the TOA when water vapor is higher or lower than the monthly average. However, since the forcing is the subtraction of fluxes in background and polluted conditions, we expect those biases in water vapor to play a smaller role in the DARF. To accurately answer this question, it would be necessary to define empirical ADMs from CERES radiance measurements, using a similar approach to the one used by Patadia et al., 2011 paper to account for aerosol anisotropy. Instead of taking aerosol variations into account, as Patadia et al., 2011 did, one could study how water vapor content modifies radiances and build flux retrievals from the new empirical ADMs. Although this could be studied in the future, we believe this approach is beyond the scope of this work.

4) In Sect. 3.3. the discussion about Figure 5 could be more concise, the different explanations could be e.g. listed and then discussed in more detail.

We thank the referee for this suggestion. The discussion about Figure 5 was reformulated, as well as section 3.3, in order to make the whole section more clear and concise.

5) Since this method defines only cloud-free smoke aerosol forcing, the authors could give a rough estimate of how large proportion of all the possible satellite overpasses are cloud-free (and cloudy) during the forest fire season over Amazonia.

Thank you for raising this important point. We've included an estimation of the percentage of cloud-free and cloudy areas over the Amazonia during the studied period, based on MODIS Level 3 cloud fraction retrievals. This product indicates that during the studied period (August to September) the cloud fraction over Amazonia is on average about 47%, during Terra morning passage (about 10:30 AM LT), increasing to about 56%, during the afternoon (Aqua passage time is about 1:30 PM LT).

Specific comments:

Sect. 4: "Validation of aerosol forcing" (also later in the Section); I would suggest to use "comparison" instead of "validation" since both the AERONET inversions and the model simulations are not "direct" measurements.

Yes, this suggestion was implemented. We have used the word "comparison" instead of "validation" throughout the text, including Section 4 title.

Figures:

Figure 1 and 4 captions: Which is the time period when these observations were collected?

In Figure 1, 4 months worth of data, from July to October, 2005, over the grid cell were used in this example. This information was included in Figure 1 caption. Figure 4 was removed from the manuscript following reviewer's #1 suggestion, but 2 months of data were used in this figure, from August to September of 2005.

Figure 6: From which data are these lines defined? (Many grid cells or one grid cell, one year or multiple years...)

This figure is just a schematic illustration of the possible issues caused by adjusting linear fits between CERES flux at the TOA and MODIS AOD from collection 4 and collection 5, used in previous studies to calculate the DARF. It is meant to explain why using MODIS collection 4 AOD could overestimate the DARF, using a previous methodology. No real data was used in this figure. We've added this information in the figure caption, in the revised manuscript, in order to make this point clear.

A novel methodology ~~using MODIS and CERES~~ for large scale, daily assess~~ing the daily~~ment of the direct radiative forcing of smoke aerosols ~~in large scale over the Amazonia~~

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Abstract

A new methodology was developed for obtaining daily retrievals of the direct radiative forcing of aerosols (24h-DARF) at the top of the atmosphere (TOA) using satellite remote sensing. ~~For that, simultaneous~~Simultaneous CERES (Clouds and Earth's Radiant Energy System) shortwave flux at the top of the atmosphere (TOA) and MODIS (Moderate Resolution Spectroradiometer) aerosol optical depth (AOD) retrievals were used. To analyse the impact of forest smoke on the radiation balance, t~~T~~his methodology ~~i~~was applied over ~~a large region of~~ the ~~Brazilian~~ Amazonia~~. We focused our studies~~study ~~on~~ during the peak of the biomass burning season ~~(August to September)~~ from 2000 to 2009.~~, to analyse the impact of forest smoke on the radiation balance.~~

To assess the spatial distribution of the DARF, background smoke-free scenes ~~without biomass burning impacts,~~ were ~~defined as scenes with MODIS AOD < 0.1~~selected. The fluxes at the TOA ~~retrieved by CERES for those~~under clean conditions (F_{cl}) were estimated as a function of the illumination geometry (θ_0) for each 0.5ºx0.5º degree~~s~~ grid cell. The instantaneous DARF was obtained as the difference between the clean ($F_{cl}(\theta_0)$) and the polluted ~~mean~~ flux at the TOA measured by CERES in each cell ($F_{pol}(\theta_0)$). The radiative transfer code SBDART (Santa Barbara DISORT Radiative Transfer model) was used to expand instantaneous DARFs to 24h averages.

~~With t~~This new methodology ~~it is possible~~was applied to assess the DARF both ~~at large scale and~~ at high temporal resolution ~~over the~~and over a large area in Amazonia. ~~This new methodology also showed to be more robust, because it considerably reduces statistical sources of uncertainties in the estimates~~estimate ~~of the DARF, when compared to previous assessments of the DARF using satellite remote sensing.~~

The spatial distribution ~~of the 24h-DARF~~ shows that~~, for some cases,~~ the mean 24h-DARF ~~presents local values~~can be as high as -30 W/m^2 over some regions. The temporal variability of the 24h-DARF along the biomass burning season was also studied and showed large intraseasonal and interannual variability. ~~In~~

an attempt to validate the radiative forcing obtained in this work using CERES and MODIS, those results were compared to coincident AERONET ground based estimates of the DARF. This analysis showed that CERES-MODIS and AERONET 24h-DARF are related as

$DARF_{CERES-MODIS}^{24h} = (1.07 \pm 0.04) DARF_{AERONET}^{24h} - (0.0 \pm 0.6)$. This is a significant result, considering that the 24h-DARF retrievals were obtained by applying completely different methodologies, and using different instruments. The instantaneous CERES-MODIS DARF was also compared with radiative transfer evaluations of the forcing. To validate the aerosol and surface models used in the simulations, downward shortwave fluxes at the surface evaluated using SBDART and measured by pyranometers were compared. The simulated and measured downward fluxes are related through

$F_{BOA}^{PYRANOMETER} = (1.00 \pm 0.04) F_{BOA}^{SBDART} - (20 \pm 27)$, indicating that the models and parameters used in the simulations were consistent. The relationship between CERES-MODIS instantaneous DARF and calculated SBDART forcing was satisfactory, with

$DARF_{CERES-MODIS} = (0.86 \pm 0.06) DARF_{SBDART} - (6 \pm 2)$. Those analysis showed a good agreement between satellite remote sensing, ground-based and radiative transfer evaluated DARF, demonstrating the robustness of the new proposed methodology for calculated We showed that our methodology considerably reduces statistical sources of uncertainties in the estimate of the DARF, when compared to previous approaches. We showed that our DARF assessments using the new methodology agrees well with other satellite remote sensing studies, ground-based measurements and radiative transfer models. This demonstrates the robustness of the new proposed methodology for assessing the radiative forcing for biomass burning aerosols. To our knowledge, this was the first time satellite remote sensing assessments of the DARF were compared with ground based DARF estimates.

1 Introduction

The Amazonia is the largest tropical rainforest of the world, occupying an area of more than 6.6 million km^2 in South America. This large ecosystem plays a crucial role in regulating global and regional climate and the hydrological cycle, powering global atmospheric circulation, transporting heat and moisture to continental areas (Artaxo et al., 2013, Davidson and Artaxo, 2004, Artaxo et al., 2013). In the last decades, anthropogenic activities, such as deforestation for agricultural and urban expansion have highly disturbed this important environment (Betts et al., 2008, Bowman et al., 2009, Davidson et al., 2012). During the wet season, the Amazon Basin is one of the few continental places of the world where we can observe pristine conditions (Andreae et al., 2007). The population of aerosols during the wet season is dominated by primary biogenic coarse mode particles (Martin et al., 2010), and presents typical concentration of about 300 particles per cm³ (Artaxo et al., 2002). This scenario changes dramatically during the dry season, with particle concentration reaching around 20,000 particles per cm³ due to biomass burning emissions (Holben et al., 1996, Echalar et al., 1998, Andreae et al., 2002, Artaxo et al., 2009, Echalar et al., 1998, Holben et al., 1996). Furthermore, not only does the absolute). This strong increase in aerosol concentration of particles strongly increases, but there are also tremendous modifications in theis accompanied by a significant modification in particle size distribution of aerosols, since most of the particles emitted during burning events belong to the fine mode (Dubovik et al., 2002, Eck et al., 2003, Schafer et al., 2008).

Aerosol particles can modify the Earth's radiative balance in two ways: i) directly, by interacting with solar radiation, through scattering and absorption processes (eg., Charlson et al., 1992, Chylek and Wong, 1995), and ii) indirectly, by modifying the microphysical structure of clouds, such as droplet size distribution~~,~~ and cloud albedo ~~and other properties~~ (eg.,~~-~~ Twomey et al., 1977, Coakley et al., 1987, Albrecht et al., 1989, Andreae et al., 2004, ~~Coakley et al., 1987,~~ Koren et al., 2008~~, Twomey et al., 1977~~). These effects depend on the concentration and on the horizontal and vertical distributions of particles in the atmosphere, on their optical properties, such as single scattering albedo, size distribution, phase function, hygroscopicity, and on the surface reflectance properties of the underlying region (eg., Haywood and Boucher, 2000; Yu et al., 2006). In particular, biomass burning aerosols play an important role in modifying the radiative energy balance of the affected region because fine mode particles interact efficiently with solar radiation (Liou, 2002).

The direct aerosol radiative forcing (DARF) in Amazonia was previously assessed using radiative transfer models coupled with ~~either~~ ground-based remote sensing ~~(~~measurements (Procopio et al., 2004) or ~~intensive~~in-site field-campaigns ~~in-situ measurements (~~(Ross et al., 1998). Although these approaches may provide detailed insight about a specific burning event~~ or a bit larger region~~, they are limited in space (in the case of ground-based studies) or in time (in the case of intensive field campaigns). As satellite remote sensing provides high spatial coverage it has been used to assess the large scale DARF. An interesting technique ~~uses~~ used CERES (Clouds and Earth's Radiant Energy System) flux at the top of the atmosphere (TOA) combined with MODIS (Moderate Resolution Spectroradiometer) or MISR (Multi-angle Imaging Spectroradiometer) aerosol optical depth (AOD) to assess the mean DARF over Amazonia during the biomass burning season and analyze~~s~~ its spatial variability (Patadia et al., 2008, Sena et al., 2013). This technique (CERES+MODIS) has also been widely applied to evaluate the mean DARF over a time period (usually 2-3 months) in several other regions (eg., ~~Christopher, 2011,~~ Zhang et al., 2005, Christopher, 2011, Feng and Christopher, 2014, Sundström et al., 2014). Although these studies focused on averages are useful, they lack the high temporal resolution needed to observe important details on the changes of the radiative balance due to the short residence time of aerosols in the atmosphere. During the dry season, aerosol residence time within the boundary layer is estimated ~~in~~to be about 4 to 6 days (Freitas et al., 2005, Edwards et al., 2006~~, Freitas et al., 2005~~). Also, biomass burning aerosols can be transported over great distances away from their sources (Andreae et al., 2001, Longo et al., 2009), depending on the prevalent dynamics in the studied area. Due to their short lifetime and to the dynamics of transport of these particles, aerosols present highly inhomogeneous spatial and temporal distributions. With that in mind, ~~this work has~~we developed a methodology for calculating the smoke DARF in Amazonia with higher spatial and temporal resolution than previous assessments (0.5ºx0.5º degrees and 1 day, respectively) using satellite remote sensing. As opposed to previous studies, that consider the total effect of aerosols (both from background and polluted conditions) on the radiative budget, this study focused on assessing the anthropogenic DARF only. This can also be regarded as an improvement over previous methodologies, since aerosol-free conditions cannot be observed in the atmosphere.

The main goals of this work were:

i) to introduce a new methodology to assess the daily direct radiative forcing of biomass burning aerosols ~~in~~ over a large scale ~~over the~~of Amazonia using satellite remote sensing (Section 2);

ii) to analyse the intraseasonal and interannual variability of the daily average DARF as well as its mean daily spatial distribution pattern over Amazonia (Sections 3.1 and 3.2);

iii) to validate the calculated DARF obtained by applying this new methodology with ground-based sensors, as well as radiative transfer DARF calculations (Section 4).

We also believe that this methodology could be easily applied to study the DARF24h in other regions of the world, impacted by biomass burning or even urban pollution.

2 Data and methods

In this work, combined CERES shortwave TOA flux ~~at the top of the atmosphere (TOA)~~ and MODIS aerosol optical depth (AOD) at 550 nm ~~retrievals~~ were used to assess the direct radiative forcing of biomass burning aerosols over the Amazon Basin for cloud-free conditions. ~~Both these~~These both instruments are aboard NASA's Terra and Aqua satellites.

CERES sensors are passive scanning radiometers that measure the upward radiance in three broadband channels: i) between 0.3 to 5.0 μm, to measure the shortwave radiation reflected in the solar spectrum; ii) between 8 and 12 μm, to measure the thermal radiation emitted by the Earth in the atmospheric window spectral region, and iii) between 0.3 and 200 μm to measure the total radiation spectrum emerging at the TOA (Wielicki et al., 1996). Radiance measurements are converted into broadband radiative fluxes through the use of angular distribution models (ADMs) (Loeb et al., 2005).

MODIS ~~sensor measure~~measures the radiance at the TOA in 36 narrow spectral bands between 0.4 and 14.4 μm (Salomonson et al., 1989). Among its various applications, MODIS observations have been widely used to monitor land surface, oceans and atmosphere properties and to provide information about ~~clouds~~cloud and ~~aerosols~~aerosol optical properties, their spatial and temporal variations, and the interaction between aerosols and clouds (King et al., 1992).

CERES Single Scanner Footprint (CERES-SSF) product provides simultaneous retrievals of the upward flux at the TOA derived by CERES on three broadband channels, and properties of aerosols and clouds reported by MODIS. In this product, MOD04 aerosol and ~~clouds~~cloud properties, that are originally reported with a 10 km spatial resolution, are reprojected to CERES 20 km resolution (Smith, 1994). Over land, MODIS's AOD uncertainty is estimated as: $\sigma_{land} = \pm 0.05 \pm 0.15 AOD_{550nm}$ (Remer et al., 2005).

For the development of the new methodology presented here, we used CERES-SSF Edition 3A shortwave flux retrievals at the TOA ~~retrievals~~ from Terra satellite over the Amazon Basin from July 1 to October 31 from 2000 to 2009. The studied area was limited between the coordinates 3°N–20°S, 45°W–65°W and

3°N–11°S, 65°W– 74°W. Pixels with 1-km resolution MODIS cloud fraction above 0.5% and with a clear area in the MODIS 250 m resolution lower than 99.9% were removed. To limit distortions we removed from our analysis pixels that presented view and solar zenith angles greater than 60°. The DARF was calculated with a 0.5° x 0.5° latitude/longitude spatial resolution, according to the methodology described in the next section.

2.1 Evaluation of the daily direct RF of biomass burning aerosols

The direct radiative forcing of aerosols (DARF) can be defined as the difference between the upward radiation flux at the TOA measured in background ~~conditions~~ (F_{cl}) and ~~in~~ polluted conditions (F_{pol}).

$$DARF = F_{cl} - F_{pol} \,. \qquad (1)$$

For each scene observed by CERES, F_{pol} can be ~~obtained~~ directly obtained from the mean flux at the TOA for each 0.5º x 0.5º grid cell. To calculate the instantaneous DARF, we need to estimate what would be the flux at the TOA for background conditions (F_{cl}) for the same illumination geometry of the polluted scene. To perform this estimate, scenes that presented aerosol optical depth (AOD) smaller than 0.1 were selected, and considered as background scenes. This threshold was selected by analysing AERONET's AOD during the wet season. For each cell, the flux at the TOA observed for background scenes (F_{cl}) during the 40-months studied period was plotted against the cosine of the solar zenith angle ($\cos(\theta_0)$). An example of this plot, for the grid cell centred at latitude 8.75ºS and longitude 53.75ºW, is shown in Figure 1. A correlation coefficient of 0.94 between F_{cl} and $\cos(\theta_0)$ was observed for the data points within this cell indicating the adequacy of the linear ~~aproximation.~~approximation. It is worth emphasizing that this example is not a best case scenario. In fact, more than 80% of the cases analysed showed a correlation larger than 0.90 between F_{cl} and $\cos(\theta_0)$.

The solar zenith angle varied from about 10° to 52° at Terra satellite passage time over the Amazonia during the ~~studied~~ study period. For this solar zenith angle range, F_{cl} varies linearly with $\cos(\theta_0)$. By adjusting a linear fit to the data points within each cell we can calculate $F_{cl}(\theta_0)$ for any illumination geometry, according to equation 2,

$$F_{cl}(\theta_0) = A\cos(\theta_0) + B \,, \qquad (2)$$

where A and B correspond to the slope and the intercept of the linear fit, respectively.

To assess the instantaneous DARF, the mean solar zenith angle within each cell during the satellite passage time was identified for every polluted scene. For each cell, the instantaneous DARF was evaluated as the difference between $F_{cl}(\theta_0)$ and the mean flux at the TOA retrieved by CERES in polluted conditions ($F_{pol}(\theta_0)$), as previously stated in equation (1). The uncertainty of the DARF in each cell (σ_{DARF}), was computed using error propagation, according to the following equation:

$$\sigma_{DARF}^2 = \sigma_A^2 \cos^2(\theta_0) + \sigma_B^2 + 2\operatorname{cov}(A,B)\cos(\theta_0) + \sigma_{Fpol}^2 , \qquad (3)$$

where σ_A, σ_B and *cov(A,B)* are the uncertainty of the slope, intercept and the covariance between the slope and the intercept, respectively; σ_{Fpol} is the uncertainty of the ~~of the~~ flux in each cell for the polluted condition.

2.2 Correction of the DARF according to empirical ADMs

As already discussed, to convert CERES ~~radiances~~radiance measurements to radiative flux at the TOA it is necessary to define the angular distribution models (ADMs) for different scenes (Loeb et al., 2005). In a recent work, Patadia et al. (2011) pointed out that the angular distribution models currently used by CERES team to derive shortwave fluxes at the TOA over land in cloud-free conditions do not take into account aerosol properties in the observed scene. This can result in large errors in the shortwave fluxes derived by this sensor for areas with high concentrations of aerosols, such as the Amazonia during the biomass burning season. To estimate the impact of the anisotropy caused by high aerosol loading on the flux at the TOA, Patadia et al. (2011) developed a methodology to obtain new empirical angular distribution models for the Amazon Basin region during the dry season. ~~For this, the~~The authors used radiance measurements obtained by CERES shortwave channel over the ~~Amazônia~~ Amazonia for different view and solar illumination geometries between 2000 and 2008. In a later work they have assessed the difference between the DARF evaluated using both, CERES ADMs and their new empirical ADMs (Patadia and Christopher, 2014). They have found that, on average, CERES DARF relates to the corrected DARF calculated with their empirical ADMs, according to the following equation:

$$DARF_{corrected} = DARF - 52.27AOD - 2.71 + 35.15AOD + 1.78 . \qquad (4)$$

The correction proposed by Patadia and Christopher (2014) was applied to the CERES-MODIS DARF estimates introduced in the previous section.

A discrete-ordinate radiative transfer (DISORT) code (Stamnes et al., 1988) was used to expand the instantaneous radiative forcing, calculated for the satellite passage time, to 24 hours averages. MODIS BRDF/Albedo Model (MCD43B1) retrievals (Schaaf et al., 2002) over the studied area were used to develop the surface albedo models used in the radiative transfer calculations. Aerosol optical properties retrieved by the AERONET (Aerosol Robotic Network) ground-based sun-photometers (Dubovik and King, 2000) located in the Amazonia during the dry season were also used in this computation. For a detailed description of the methodology used to perform this expansion please refer to Sena et al. (2013).

3 Results and discussions

In this section we will present and explore the main results obtained by applying the methodology introduced in section 2.1 to assess the DARF. Some examples of the spatial distribution and the temporal variability of the 24h-DARF along the biomass burning season are shown and discussed in the next subsections. In section 3.3, the average of the DARF during the biomass burning season of each year is computed and compared with previous DARF results.

3.1 Examples of the spatial distribution of the 24-h DARF

~~Aerosols~~In Brazil, most fires occur on the Southern and Eastern borders of the Amazon Basin, in a region known as the "arc of deforestation"~~ (Morton et al., 2008), at the border of the Amazon forest and the cerrado (savanna-like vegetation)~~ (Malhi et al., 2008, Morton et al., 2008). ~~Due to the predominantly~~ During the dry season low level Easterly winds ~~in this region~~are dominates the atmospheric circulation over central South America (Nobre et al., 1998) ~~at low altitudes (Freitas et al., 2009),~~. Due to this dynamical feature, ~~most~~smoke particles are transported towards the forest and the Andes mountain range, where ~~both~~ eventually wind direction changes~~ and velocity change~~ (Freitas et al., 2009). Biomass burning aerosols can be transported over long distances away from their sources ~~and, therefore, can~~(Andreae et al., 2001, Freitas et al., 2005, Longo et al., 2009, Mishra et al., 2015) and cover large areas of up to millions of km^2 (Prins et al., 1998). Aerosol transport during the biomass burning season can significantly modify the spatial distribution of the DARF from one day to another. Two examples of the spatial distribution of the 24-h DARF, for 08/13/2005 and 08/15/2005, are shown in Figure 2, with their respective uncertainties. Composite images from MODIS's red, blue and green spectral channels, are also shown in this figure.

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Figure 2 shows that, on August 13th, 2005, the smoke plume covers a large area of the Brazilian Amazonia, between 4ºS and 12ºS and 55º and 70ºW. The 24-h DARF over the area was particularly high for that day, varying from about -~~15~~30 to -~~30~~15 W/m². On August 15th, 2005, we note that the smoke plume has moved Southeast, following the Andes mountain range line, strongly impacting the Southern Amazonia, Western Bolivia and Northern Paraguay. The area located between 8ºS and 20ºS and 57ºW and 65ºW showed the highest 24-h DARF values for that day, also ranging from -~~15~~30 to -~~30~~15 W/m². The 24h-DARF showed in Figure 2b was, on average, -14.3 $\pm$ 0.3 W/m² on August 13th and -15.6 $\pm$ 0.3 W/m² on August 15th. These results clearly show the importance of wind circulation in the transport of aerosol plumes and how atmospheric dynamics may influence the shortwave radiative balance of the region.

3.2 Temporal variability of the DARF along the biomass burning season

Due to the short lifetime of aerosols in the atmosphere, the DARF may vary largely along the 2-months of the biomass burning season. To analyze this temporal variability, the average of the 24-h DARF over the studied area was calculated for each day of the year. Examples of the time series of the mean daily DARF during the biomass burning season ~~of 2005, 2006 and 2007 are illustrated in Figure 3~~from 2000 to

2009 are illustrated in Figure 3. Due to a problem in CERES-SSF data processing, the year 2004 presents a high amount of missing values for aerosol and cloud properties in its database. Therefore this year was not included in Figure 3, nor in the forthcoming analysis.

Figure 3 shows that, besides its large interannual variability, the DARF also varies widely along the biomass burning season. Different temporal patterns along the biomass burning season are observed depending on the year. For example, for most of 2005's dry season, the DARF showed little variation, averaging around -9 $\pm$ 2 W/m². On the other hand, in 2007, the DARF became gradually more negative, starting around 0 W/m² in the beginning of August and reaching values of the order of -25 W/m² at the end of September. However, 2005 and 2007, both, present similar mean 24-h DARF during the burning season, as will be shown in the next section (Figure ~~5~~4). The temporal variation pattern during the biomass burning season of 2006 presents an intermediate trend to those observed in 2005 and 2007. ~~That is, the~~In 2006, ~~T~~the DARF ~~becomes more negative~~decreases until the beginning of September, when it saturates and finally ~~turns less negative. The DARF variations from one day to the other, shown in these figures, are due to changes in cloudiness and at the area scanned by MODIS, that varies according to the satellite track.~~increases once again.

The interannual variability of the DARF can also be observed. The impact of smoke aerosols in the radiative balance of 2005 and 2007 was very pronounced, while the DARF was very close to zero during the whole biomass burning season of 2009. Changes in rainfall patterns play a major role to the interannual variabilibity of the DARF. The high DARFs in 2005 and 2007 are associated with severe droughts that contributed to forest and savanna fires and high aerosol loadings in these years (Marengo et al., 2008, Ten Hoeve et al., 2012). On the other hand, the rainfall over the Amazonia in 2009 was extremely high (Satyamurty et al., 2013), which contributed to the decrease in the number of fire sources and the efficient removal of smoke aerosols from the atmosphere.

The daily DARF variations from one day to another, shown in th~~ese~~is figure~~s~~, are mainly due to changes at the MODIS imaged area, that varies according to the satellite track. Due to its polar orbiting track, every day the scanned area slightly changes, finally repeating itself after about 16 days. Depending on Terra track, for some cases MODIS doesn't cover areas heavily impacted by smoke aerosols, and the mean 24h-DARF could be underestimated. The daily DARF variation is also influenced by changes in fire sources location, transport and cloud coverage along the biomass burning season.

3.3 Average of the DARF during the biomass burning season

In previous studies (Patadia et al., 2008, Sena et al., 2013), the average of the direct radiative forcing of aerosols during the biomass burning season over the Amazonia was also calculated by using CERES and MODIS sensors. In those approaches, the average flux for clean conditions during the biomass burning season ($BBSF_{cl}$) for each cell grid was estimated from the intercept of the regression between TOA fluxes and AOD retrievals from August to September~~ (Figure 4).~~. The mean DARF during the biomass burning season (BBSDARF) was then calculated by subtracting the mean flux at the TOA ($BBSF_{pol}$) from the mean flux for clean conditions ($BBSF_{cl}$) observed as averages during ~~the~~ this two-months ~~studied~~ study period. The DARF calculated using this methodology considers the total effect of aerosols. Since the flux for clean conditions (F_{cl}) is defined for AOD=0, the effect of smoke aerosols cannot be isolated from the effect of background aerosols. Thus the total effect of aerosols from both background and polluted conditions are included in the BBSDARF.

The new methodology introduced here (Section 2.1), provides the 24h-DARF for each individual day of the year, that is, in a much higher temporal resolution than the one used in previous studies. with a much higher temporal resolution than the one used in previous studies. Furthermore this new methodology considers a more realistic clean condition, by defining F_{cl} in the presence of background aerosols. Since background aerosols are always present in the atmosphere, the contribution of background aerosols to the radiative balance should not be considered as forcing in the strict sense. In fact, some authors define the contribution of background + polluted aerosols as the direct radiative effect instead of direct radiative forcing (eg., Yu et al., 2006).

In this section we aim to compared the DARF obtained using the new methodology introduced in section 2.2 with the seasonal DARF values calculated previously by Sena et al., 2013. For this comparison, the daily DARF, obtained in this work, was averaged between the months of August and September of each year ($\langle 24hDARF \rangle_{BBS}$). To ensure that we make a fair comparison, the corrections proposed by Patadia and Christopher (2014), and used for the evaluation of the 24h-DARF in this paper (Section 2.2), were also applied a posteriori to the Sena et al., 2013 seasonal forcing (BBSDARF). Figure 54 shows the mean AOD at 550 nm during the biomass burning, and the comparison between $\langle 24hDARF \rangle_{BBS}$ and BBSDARF, calculated over the studied area, from 2000 to 2009. Once again, 2004 was excluded from the analysis, due to theCERES-SSF database problems mentiondiscussed in the previous section.

Figure 54 shows that the $\langle 24hDARF \rangle_{BBS}$ is consistentlyalways lower than the BBSDARF. The average of the BBSDARF for this 10-year period (2000 to 2009) wasis -8.2 ± 2.1 W/m², while the 10-year average of the $\langle 24hDARF \rangle_{BBS}$ was smaller at is -5.2 ± 2.6 W/m². Part of thisTwo factors contribute to theseis difference may be explained by : i) the different references were used forat the evaluation of the flux for clean assessment of the clean flux, F_{cl}, in each methodology (AOD=0 vs. background conditions. In the old methodology used by Sena et al., 2013, $BBSF_{cl}$ was defined considering AOD = 0, since the clean condition was chosen as the intercept between fluxes), and AOD=0. This methodology leads to the effect that the contribution of background aerosols (AOD approximately 0.1) was not accounted for in the final evaluation of BBSDARF. On the other hand, in the new methodology introduced here, F_{cl} was defined specifically for more realistic background conditions, according to section 2.1. Therefore, it was expected that the $\langle 24hDARF \rangle_{BBS}$ would be less negative than the BBSDARF. ii) how different aerosol collections CERES-SSF product provides an older MOD04 collection before 2005, and this strongly from MODIS affects the BBSDARF retrievals by both methodologies. In the following paragraphs, these DARF differences and their sources will be further explainored.

Radiative transfer calculations done with SBDART (Santa Barbara DISORT Radiative Transfer model) (Richiazzi et al., 1998) calculations suggest that the contribution of background aerosols at AOD=0.1 to the 24h-DARF over the Amazonia is about -2 W/m². ThereforeHence, the contribution of background aerosols may explain the magnitude of the differences in the radiative forcings obtained from 2005 on, but not before that year. Part of the DARF differences observed from 2000 to 2003, are most certainlyvery likely associated with the aerosol optical properties contained in CERES-SSF product, Edition 3A, that was used both in this work and by Sena et al. (2013). This product provides aerosol optical properties calculated using MODIS aerosol algorithm MOD04 - collection 4 until mid-2005, and MOD04 - collection 5 after that date. A major difference between theaerosol optical depths obtained by these two collections, is due to the fact that collection 4 does not allow negative values of AOD, while for collection 5, the lowest limit for the AOD is -0.05, to account for the uncertainty of the retrieved AOD. Therefore, for low aerosol loading, when AOD from MOD04 - collection 4 is projected to CERES lower resolution, it may be overestimated, since negative AOD values were removed from the average. Thus, when applying the methodology used by Patadia et al. (2008) and Sena et al. (2013), to CERES-SSF data that contained MOD04 - collection 4 AOD, the $BBSF_{cl}$ is underestimated and, therefore, the BBSDARF is overestimated (Figure 65). This explains the differences between both DARF evaluations observed in Figure 54.

The solar zenith angle strongly influences the upward flux at the TOA (F_{TOA}). CERES fluxes retrievals obtained over the same surface, for the same aerosol loading and same atmospheric conditions, and at different illumination geometry will present different F_{TOA}. In the previous methodology used in Sena et al., 2013, two months of data were used to estimate the BBSDARF through the linear fit of F_{TOA} by AOD. Thus, flux measurements performed on different days and at different times (and therefore different solar zenith angles) contributed to increase the dispersion of the points on the y axis, increasing the uncertainty of BBSDARF (Figure 4).. In the new methodology, the DARF is obtained as a function of the solar zenith angle, which eliminates the noise caused by solar zenith angle variations, observed in previous studies. This was another important improvement of the methodology proposed in this work over the previously used methodology.

It is also important to emphasize that both methodologies are applied only in cloud-free conditions. MODIS Level 3 cloud fraction retrievals indicate that during the study period (August to September) the cloud fraction over Amazonia is on average about 47%, during Terra morning passage (about 10:30 AM LT), increasing to about 56%, during the afternoon (Aqua passage time is about 1:30 PM LT). Therefore, the mean $\langle 24hDARF \rangle_{BBS}$ over the whole study area weighted by cloud cover is about -2.6 W/m^2.

The mean correlationscorrelation between the AOD 550 nm and the $\langle 24hDARF \rangle_{BBS}$ from 2000 to 2009 wasis -0.86 ± 0.03, higherwhich is better than the mean correlationscorrelation between the AOD and BBSDARF previously obtained, of -0.75 ± 0.05. This is another indication that the new daily methodology proposed here is more robust to evaluate the DARF than the seasonal averaged methodology used in previous studies.

4 ~~Validation of aerosol~~Comparison between satellite and ground-based direct radiative forcing

The methodology proposed in this work uses upward TOA ~~fluxes~~flux estimates from CERES-MODIS sensors aboard Terra for evaluating the DARF over the Amazonia and cerrado regions. As CERES ~~rely~~relies on angular distribution models (ADM) for estimating the upward flux at the TOA, it is very hard to ~~really~~ validate those flux ~~retrieval~~retrievals. Up to date, the validation of these TOA fluxes has only been made indirectly, by comparing TOA fluxes retrieved by broadband radiometers aboard different satellites (Loeb et al., 2007). As previously discussed, the use of different ADMs to convert broadband radiance measurements into flux may introduce large differences in the ~~DARF~~ calculated DARF using satellite remote sensors (Patadia and Christopher, 2014). We have applied a correction to the DARF based on Patadia et al. (2011) empirical ADMs that ~~account~~accounts for the influence of aerosols in the anisotropy of scattered radiation. Nevertheless, those new angular distribution functions are also not validated and, since there are no instruments that directly measure the upward flux at the TOA, it is not possible to truly validate neither CERES ADMs nor Patadia's empirical ADMs.

As an attempt to indirectly validate the DARF results obtained here, we compared the DARF, calculated in this work, with both ground-based measurements and radiative transfer ~~models~~ forcing estimates. In section 4.1 we analyzed the intercomparison between CERES-MODIS forcings, with those reported by AERONET's (AErosol RObotic NETwork) radiative forcing product. In section 4.2, CERES-MODIS forcings ~~are also~~were compared with radiative forcing evaluations computed using SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer model) radiative transfer code (Richiazzi et al., 1998).

4.1 Intercomparison between CERES-MODIS and AERONET 24-h DARF

AERONET is one of the most successful ground-based global networks of sun/sky radiometers for studying and monitoring aerosol physical properties around the world (Holben et al., 1998). Direct and almulcantar measurements from AERONET radiometers are used to retrieve ~~the~~ AOD and several column averaged aerosol optical and physical properties in different spectral bands. Extinction measurements on the spectral channel centered at 940 nm are used to assess column water vapour (Halthore et al., 1997). In its inversion product version 2.0, AERONET provides cloud-free sky DARF estimates~~. These DARF estimates are~~ evaluated using the radiative transfer code GAME (Global Atmospheric Model) (Dubuisson et al., 1996). The aerosol and surface models used in GAME are based on mean column averaged aerosol optical properties retrieved by AERONET's inversion algorithm (Dubovik and King, 2000) and surface properties retrieved by MODIS bidirectional reflectance product (Lucht et al., 2000, Schaaf et al., 2002), respectively.

The CERES-MODIS DARF, calculated according to the methodology described in section 2.1, was compared with the DARF reported by AERONET's inversion product. For this, we selected forcing results, located within ±25 km of the AERONET sites that ~~were operating~~ operated in the Amazonia during the ~~studied~~ study period (Abracos Hill, Alta Floresta, Balbina, Belterra, Cuiabá, Ji-Paraná and Rio Branco). AERONET's almulcantar measurements~~sunphotometers, only perform the almulcantar measurements~~, needed to calculate the radiative forcing, are made only when the solar zenith angle is larger than 50º.

However, during the dry season, at the time Terra overpasses the ~~studied~~ study region (around 10:30 local time), the solar zenith angle is on average around 33°. For this reason, there were no coincident instantaneous DARF retrievals from CERES-MODIS radiometers and AERONET sunphotometers. To compare the results, the instantaneous DARF, obtained by both CERES-MODIS and AERONET, were expanded to 24-h average DARF using the methodology described in Sena et al., 2013. A comparison between the 24h-DARF at the TOA obtained using AERONET and CERES-MODIS is shown in Figure ~~7~~6.

By applying a linear fit to the data points of Figure ~~7~~6, we see that the 24h-DARF derived from CERES-MODIS relates with the 24h-DARF reported by AERONET through the following equation:

$$DARF^{24h}_{CERES-MODIS} = (1.07 \pm 0.04)DARF^{24h}_{AERONET} - (0.0 \pm 0.6) . \qquad (5)$$

According to this equation, the ~~slope of the regression~~ agreement between CERES-MODIS and AERONET 24h-DARF is ~~compatible with 1~~acceptable within ~~2 uncertainties and the intercept is zero.~~the standard deviations of the fitted parameters. This is a remarkable result, since the 24h-DARF retrievals, showed in Figure ~~7~~6, were obtained by applying completely different methodologies, and using different instruments. AERONET sunphotometers ~~were~~are at ~~ground level,~~the surface and CERES-MODIS ~~were~~instruments are at 705 km~~,~~ aboard Terra satellite both looking at the atmospheric column. Besides that, as explained above, the instantaneous observations that were used to calculate the 24h-DARF, compared in our analysis, were performed at different hours of the day. All those differences contribute to the dispersion of about 5 W/m² around the adjusted line. The uncertainties involved in the surface and aerosol optical models used in GAME's radiative transfer code to calculate ~~the~~ AERONET's DARF ~~reported by AERONET~~ can also contribute ~~somewhat~~ to this dispersion. These results indicate a high agreement between the 24h-DARF obtained by these two independent procedures.

4.2 Intercomparison between CERES-MODIS and SBDART Instantaneous DARF

It is also important to intercompare satellite remote sensing retrievals with ground based measurements. In order to properly do that ~~it was compared~~, we compare CERES-MODIS ~~determinations~~data at the TOA with SolRad-NET (Solar Radiation Network) pyranometers at the bottom of the atmosphere (BOA), using SBDART calculations to link BOA to TOA. To formulate the surface models used in SBDART, we selected 50 km x 50 km areas centred at the AERONET stations~~,~~ listed in Section 4.1. For each selected area, the spectral surface albedo was obtained from the linear interpolation of MODIS MCD43B1 surface albedo retrievals in 7 wavelengths (Lucht et al., 2000, Schaaf et al., 2002). The aerosol models used in these simulations were built using ~~D~~daily averages of intrinsic aerosol optical properties retrieved by AERONET ~~inversion product were used to define the aerosol models used in these simulations~~. The aerosol optical depth and column water vapour measured by AERONET sunphotometers within ±1/2 hour of Terra's timepass over each site were also used as inputs in the radiative transfer code. The shortwave downward flux at the surface and the DARF at the TOA were computed ~~with~~ by SBDART and compared with ground-based sensors solar flux measurements and with CERES-MODIS DARF, respectively.

Figure ~~8~~7 shows the comparison between the downward flux at the surface ($F_{\downarrow BOA}$) calculated by SBDART between 0.3 and 2.8 μm and coincident solar flux measurements at the surface in the same spectral range from SolRad-NET pyranometers, that are collocated with AERONET sunphotometers. A linear fit of the downward flux measured by the pyranometer at the surface ($F_{BOA}^{PYRANOMETER}$) and calculated by SBDART (F_{BOA}^{SBDART}) indicate that these variables are related through the following equation:

$$F_{BOA}^{PYRANOMETER} = (1.00 \pm 0.04) F_{BOA}^{SBDART} - (20 \pm 27) \,. \qquad (6)$$

~~According to the adjusted parameters of this fit and their uncertainties, the slope and intercept of the linear fit (equation 6) are compatible with 1 and 0, respectively, within one uncertainty.~~ Equation 6 shows that the agreement between calculated and measured BOA fluxes is acceptable within the standard deviations. The apparent mismatch of about 20 W/m² between the calculated and measured values represents approximately 2.2% of the downward flux at the surface, and this is close to the instrumental uncertainty of the pyranometer, reported as 2%. These results show a good agreement between the downward irradiance at the surface, calculated using SBDART and SolRad-NET ~~pyranometers~~pyranometer measurements.

The intercomparison between the instantaneous TOA DARF obtained using CERES-MODIS and calculated using SBDART is shown in Figure ~~9~~8. The data points in this graph have a dispersion of about 10 W/m² around the 1:1 line. A linear fit of the data plotted in Figure ~~9~~8 shows that the instantaneous TOA DARF obtained from CERES-MODIS and from SBDART relate through the following equation:

$$DARF_{CERES-MODIS} = (0.86 \pm 0.06) DARF_{SBDART} - (6 \pm 2) \,. \qquad (7)$$

~~indicating that the curve obtained by linear regression of the points is close to y = x line for the range of values analysed.~~

Several issues in this comparison must be taken into account. First the upward flux is strongly influenced by the surface reflection. MODIS sensor presents low spectral resolution in the shortwave spectrum and this limits the surface albedo model used as input in SBDART. Secondly, the atmosphere has to be taken into account twice: on the downward and upward path. This amplifies any inaccuracy in the optical properties assumed in the SBDART calculations.

Small deviations in the estimates of aerosol single scattering albedo can generate large differences in the forcing calculated by radiative transfer codes (Loeb and Su, 2010, Boucher et al., 2013). To assess the impact of the uncertainties associated with different single scattering albedo values, the 24h-DARF was computed in SBDART as a function of AOD at 550 nm for different values of single scattering albedo at 440 nm (ω_0=0.89, 0.92 and 0.95) (Figure ~~10~~9). The differences of $\pm$0.03 ~~for~~ in ω_0, used in these simulations, correspond to the uncertainty of the single scattering albedo inverted by ~~the~~ AERONET ~~algorithms~~. ~~According to Figure 10, a variability of 0.03 in the estimate of the single scattering albedo can generate a difference in the computed 24h-DARF of about 5 to 6 W/m² when AOD=1 and 12 to 14~~

W/m² when AOD=5. These values are very significant, and shows that the critical parameter in assessing the correct DARF is actually the aerosol single scattering albedo.

According to Figure 9, a variability of 0.03 in the estimate of the single scattering albedo for the mean AOD observed over the Amazonia (0.2 to 0.4) would affect the 24h-DARF in about 1 to 2 W/m^2. To evaluate if these values are consistent with the 24h-DARF variation observed withby AERONET, the database was divided in AOD bins of 0.05 and the standard deviation of AERONET's 24h-DARF on each bin was analyzed. This analysis showed that for AOD varying from 0.2 to 0.4, the standard deviation of the AERONET 's 24h-DARF on each bin varied between 1.5 and 2.7 W/m^2. This variation is higher than the one obtained using SBDART, because in those simulations, only single scattering albedo was varied and other aerosol and atmospheric properties were fixed. However, there are other variables that influence the 24h-DARF observed by AERONET besides single scattering albedo, such as scattering phase function, size distribution and atmospheric water vapor content. These values are very significant and they show that aerosol single scattering albedo is a critical parameter to accurately assess DARF.

Considering all potential sources of uncertainties on the aerosol and surface albedo models used in SBDART simulations onto computing compute the DARF, it is possible to consider the validationcomparison showed on Figure 98 as satisfactory. It is important to note that this validation consistconsists of an indirect comparison, since, as previously discussed, it is not possible to obtain the flux at the TOA by direct methods.

5 Summary and conclusions

This work proposed a new methodology for assessing the direct radiative forcing of biomass burning aerosols in over a large scale area over theof Amazonia using satellite remote sensing. Ten years of simultaneous CERES and MODIS retrievals, from 2000 to 2009, were used in this evaluation. An important correction (Patadia and Christopher, 2014) was applied to the DARF, to account for the anisotropic scattering of smoke aerosols.

The spatial and temporal distributions of the mean daily DARF were analysed. Those analysis showed that due to the wind dynamics and fast transport of particles along the Amazon Basin, the spatial distribution of the DARF may considerably change even during short periods of time. The DARF varies strongly along the biomass burning season, showing up to 20 W/m² daily variation. The intraseasonal behaviour of the DARF also varied significantly from year to year due to different burning intensity associated with different climatic conditions and other socioeconomical changes (Davidson et al., 2012).

The average of DARF during the biomass burning season were computed and compared with DARF results obtained in a previous study (Sena et al., 2013). This comparison showed a mean difference of about 3 W/m^2 on the DARF, depending on the methodology applied. This difference was mainly caused by two factors: i) the difference in the reference used to represent the clean scene in these two methodologies, and ii) the fact that, before 2005, CERES-SSF product contains properties of aerosols from an older MODIS collection (collection 4), which overestimates the forcing computed for those years when the previous methodology ~~in~~is applied.

An important part of our efforts focused on linking satellite remote sensing with ground based aerosol and radiation flux measurements. The ~~intercomparison between~~ DARF ~~results assessed~~evaluated using the new methodology proposed in this work~~,~~ was compared with AERONET and SBDART DARF assessments. The results obtained from those intercomparisons were very satisfactory. This ~~validation~~comparison also indicates the importance of taking into account the angular distribution model corrections proposed by Patadia and Christopher, 2014, and used in the present study. To our knowledge, this was the first time satellite remote sensing assessments of the DARF were compared with ground based DARF estimates.

The new methodology introduced in this work ~~assesses the radiative~~provided a large scale assessment of the direct radiative forcing of biomass burning aerosols over the Amazonia ~~in large scale and~~ at higher temporal resolution than previous studies. It also show~~s~~ed an advantage over previous approaches for evaluating the DARF using satellite remote sensing, because it considerably ~~decreases~~ reduces the statistical noise in the estimates of the DARF, resulting in ~~higher~~a better correlation between DARF and AOD, compared to previous assessments. This new methodology could also be applied to assess the DARF in other places of the world under urban or biomass burning aerosol influences, if suitable and robust aerosol optical parameters are available.

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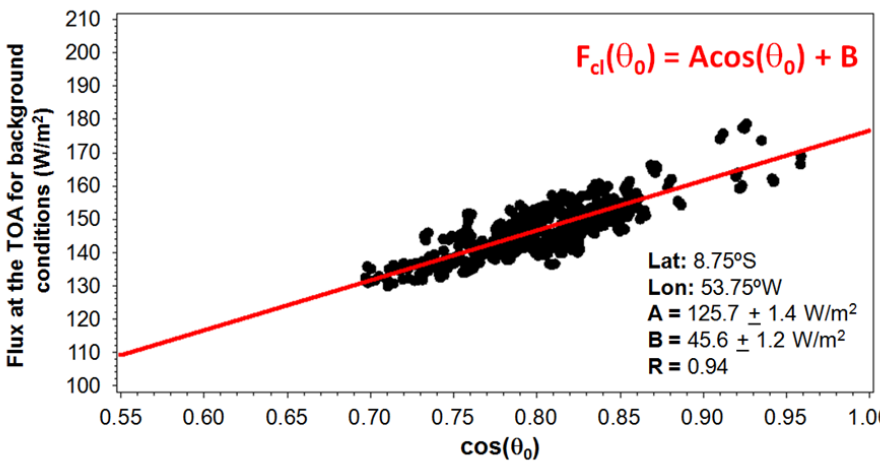


Figure 1: Example of the procedure used to obtain the flux at the top of the atmosphere (TOA) for background conditions (F_{cl}) as a function of the solar zenith angle (θ_0) for a 0.5º x 0.5º cell located in the Amazon Basin. In this example, four months worth of data over the grid cell were used, from July to October, 2005.

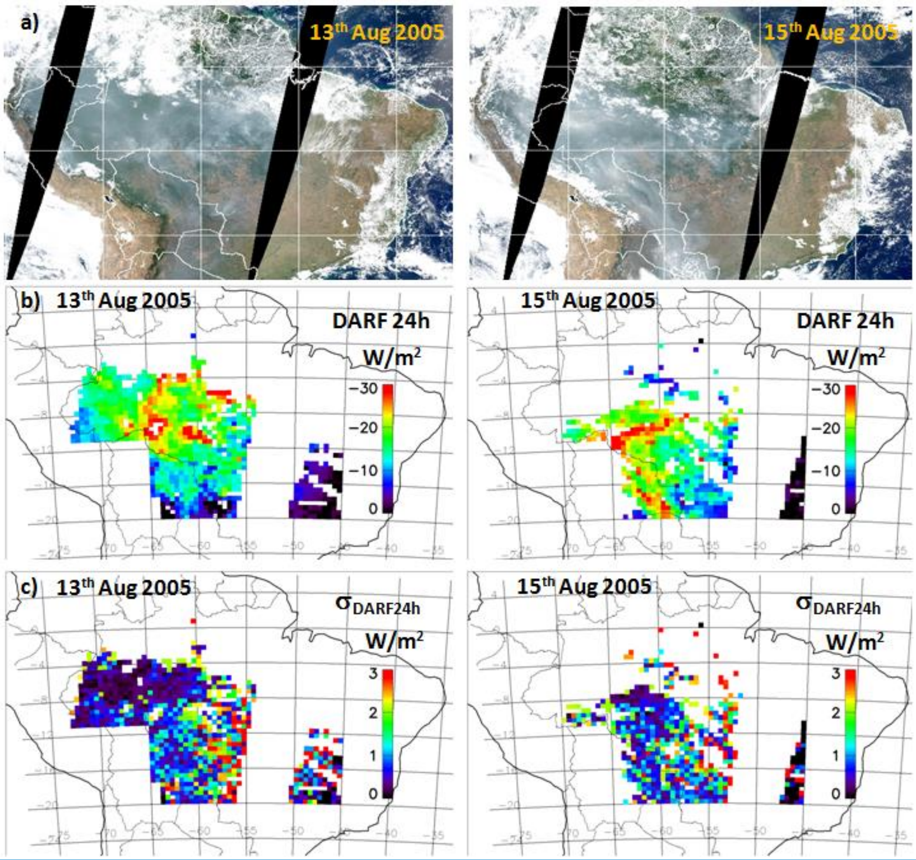


Figure 2: (a) Examples of composite MODIS RGB (red, green, blue) images over the Amazonia, (b) mean daily spatial ~~distribuitions~~distributions of the direct aerosol radiative forcing of aerosols (DARF24h), (c) and their uncertainties for 13th August 2005 (left) and 15th August 2005 (right).

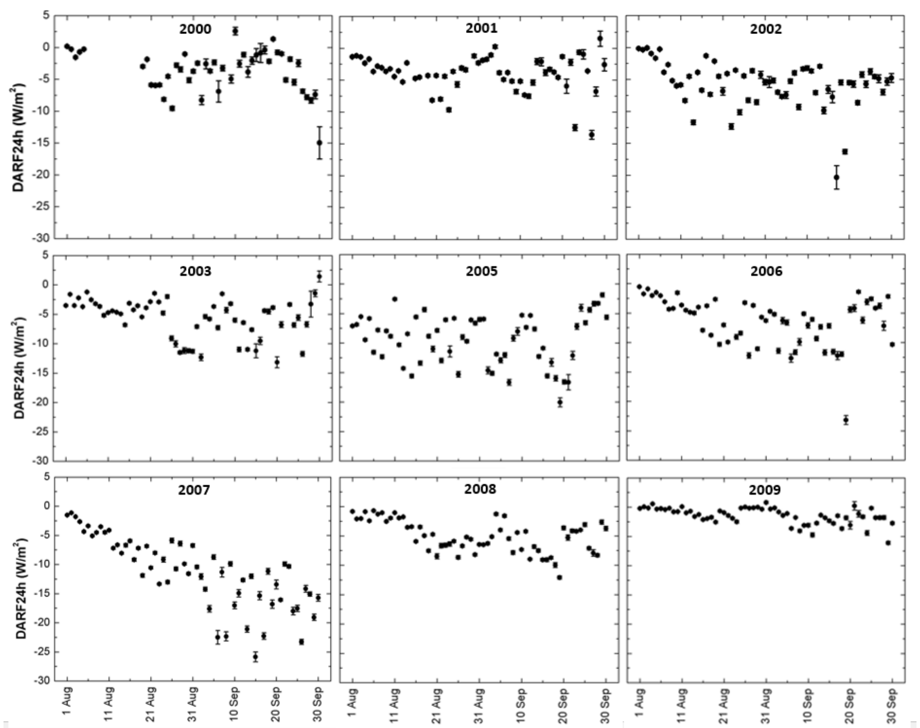
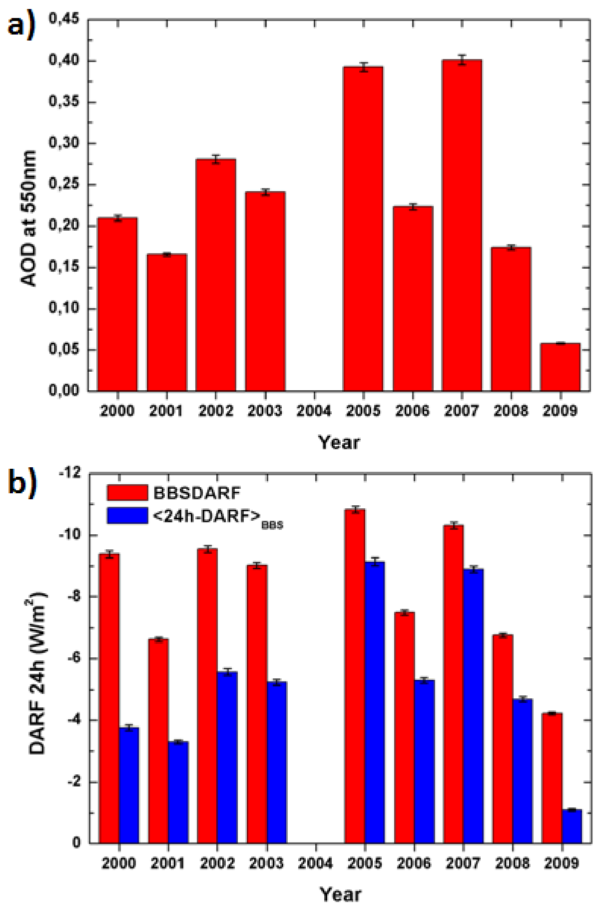


Figure 3: Temporal variability of the direct radiative forcing of aerosols (DARF24h) along the biomass burning season for: (a) 2005, (b) 2006 and (c) 2007.

~~Figure 4: Example of the methodology previously used (eg., by Patadia et al., 2008 and Sena et al., 2013) to estimate the average of the DARF during the biomass burning season (BBSDARF) using CERES and MODIS sensors.~~



~~Figure 5~~Figure 4: (a) MODIS mean aerosol optical depth at 550 nm over Amazonia during the dry season (b) and mean direct aerosol radiative forcing of aerosols (DARF24h) during the peak of the biomass burning season (August to September) from 2000 to 2009 obtained by the methodology applied by Sena et al., 2013 (BBSDARF) and by the methodology proposed in this work ($\langle 24hDARF \rangle_{BBS}$).

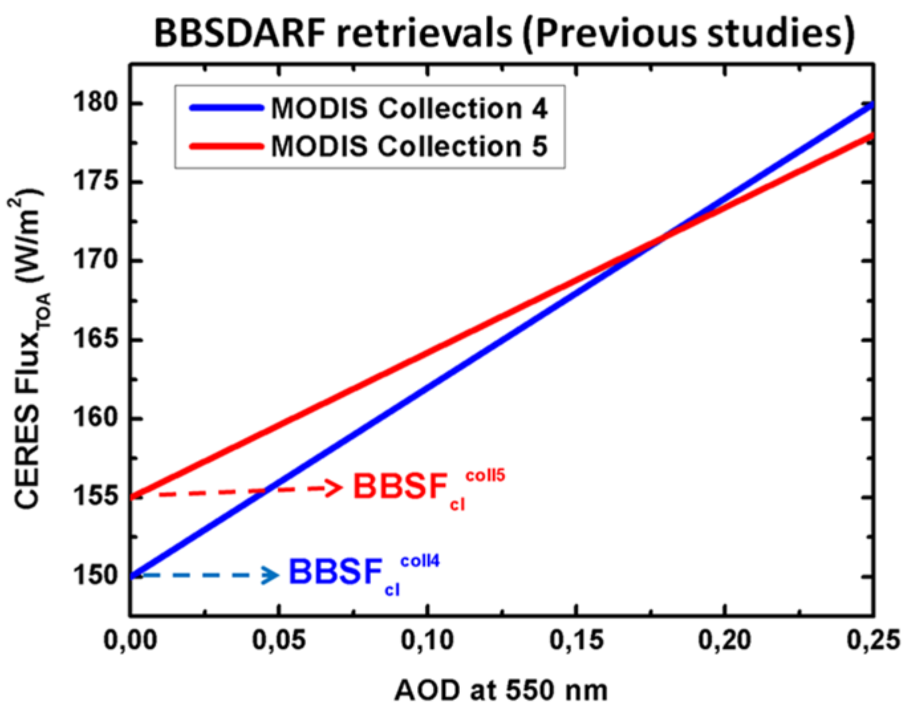


Figure ~~6~~5: Schematic illustration of the differences in the linear fits of CERES flux at the top of the atmosphere (TOA) and MODIS collection 4 and collection 5 aerosol optical depth (AOD) at 550 nm. No real data was used in this figure.

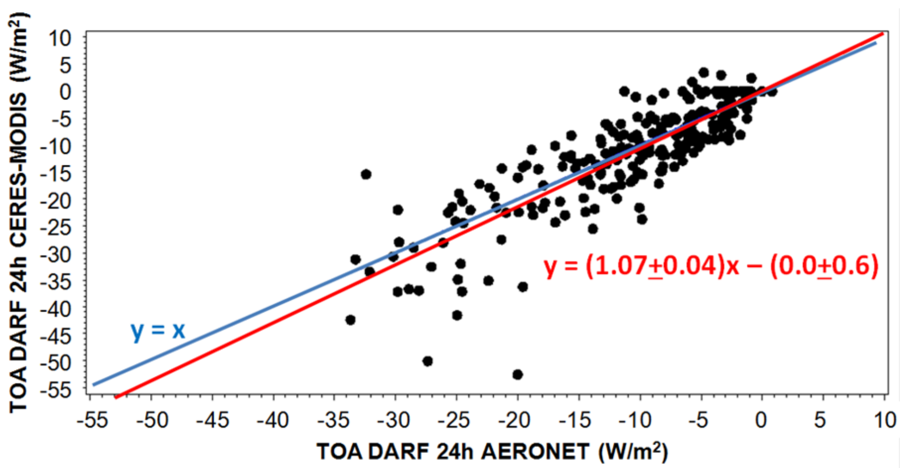


Figure ~~7~~6: Intercomparison between the mean daily direct radiative forcing (DARF24h) at the top of the atmosphere (TOA) evaluated using CERES-MODIS and by AERONET inversion product.

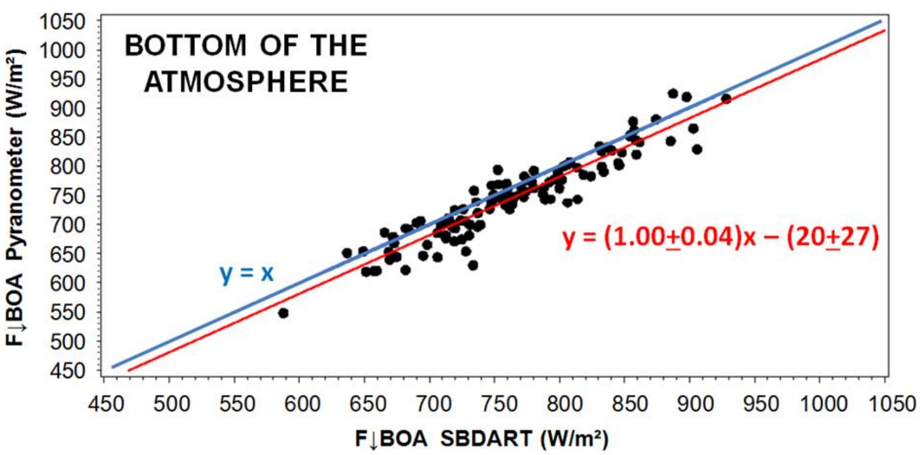


Figure ~~8~~7: Intercomparison between the incoming flux in W/m² at the bottom of the atmosphere (BOA) measured by SolRad-NET pyranometers and modelled using AERONET and MODIS BRDF retrieved optical properties as inputs in SBDART.

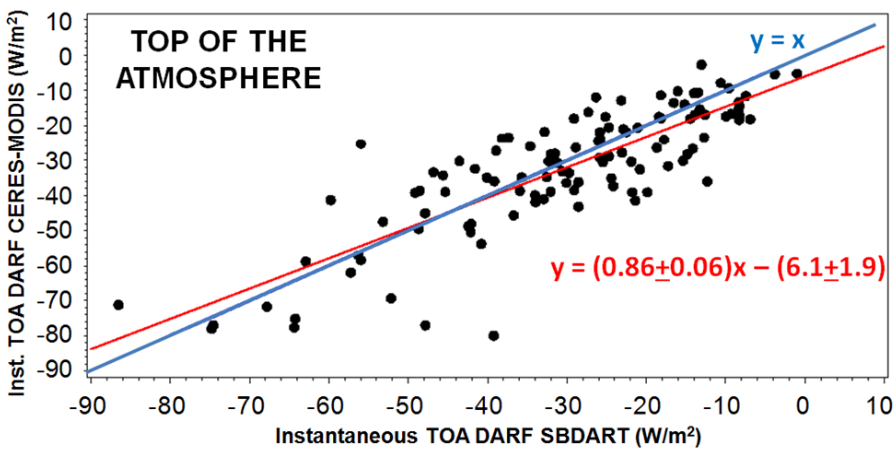


Figure 98: Intercomparison between the instantaneous direct aerosol radiative forcing (DARF) at the top of the atmosphere (TOA) evaluated using CERES-MODIS and modelled using AERONET and MODIS BRDF retrieved optical properties as inputs in SBDART.

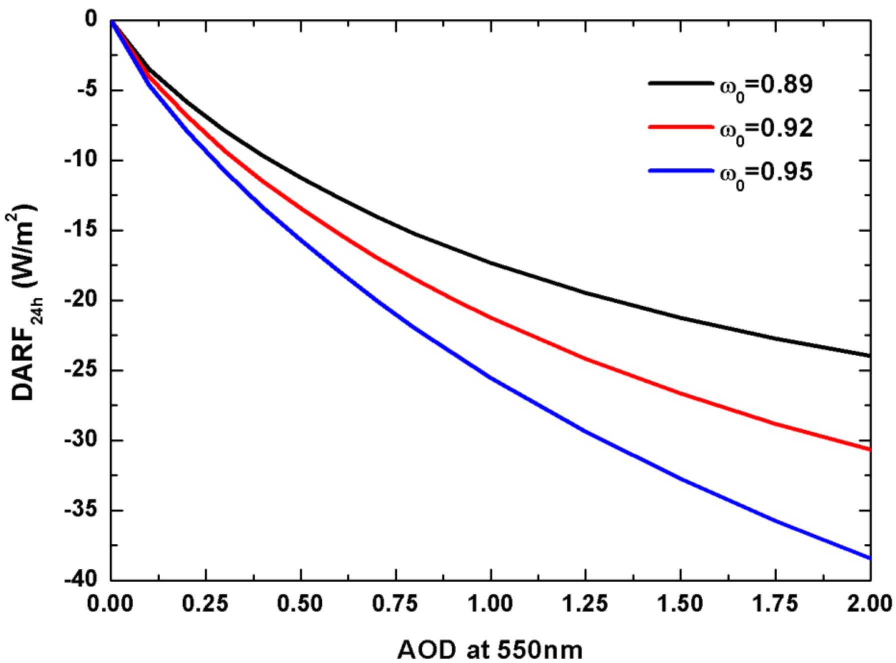


Figure ~~10~~9: Direct radiative forcing of biomass burning aerosols (DARF24h) over the forest as a function of aerosol optical depth (AOD) at 550 nm and single scattering albedo (ω_0) at 440 nm according to radiative transfer calculations.