Initial approach in biomass burning aerosol transport tracking with CALIPSO and MODIS satellites, sunphotometer and a backscatter lidar system in Brazil

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ABSTRACT

Nowadays there is an increasing concern about the direct and indirect influence of the aerosols in the Earth's radiative budget. Aerosols from biomass burning activities have been identified as a significant radiative forcing agent. A significant concentration quantity of aerosol particles observed in the atmosphere can be associated with intense anthropogenic biomass burning activity. The CALIPSO satellite and ground-based Lidar systems are indispensable to provide the vertical structure and optical properties of aerosol and clouds on global and local scale, respectively. The Brazilian mid-western region is one of the biggest producers of biomass burning in the whole continent. Aerosols from biomass burning can be transported to distances of hundreds or thousands of kilometers. It has been developed a computational routine to map the CALIPSO overpasses over the whole country in order to retrieve the total coverage taking special attention in the Brazilian AERONET sites. In this context, the measured data from AERONET, CALIPSO and MODIS Satellite and the MSP-Lidar system from Instituto de Pesquisas Energéticas e Nucleares (IPEN) can be used to map the aerosols biomass burning plumes transported from the mid-western to the southeastern region. In total 5 sites were chosen spanning from 0 to 23 South latitude and 46 to 60 West in longitude in coverage during 2007 and we were able to identify such transports during the months of August and September.

Keywords: LIDAR, CALIPSO Satellite, MODIS Satellite, Sunphotometer, biomass burning aerosol

1. INTRODUCTION

Nowadays there is an increasing concern about the direct and indirect aerosol effects on climate changes. According to the Intergovernmental Panel on Climate Change report, 2007 (IPCC, 2007) the aerosol and clouds radiative effects are the largest uncertainties in the understanding in the climate change studies. Therefore, accurate measurements and more detailed studies are extremely important in determination of direct and indirect influences of natural and anthropogenic aerosols in the atmosphere.[1] Several efforts have been done to improve the measurements of horizontal, vertical and temporal distribution of aerosol particles on the local and global scales and to achieve a better understanding of the optical properties of different types of aerosol. In order to develop a local to regional monitoring of aerosol there are several ground-based networks spread all over the world such as the Aerosol Robotic Network (AERONET)[2] ,an optical ground-based aerosol monitoring network and data archiving system, which provides globally distributed observations of aerosol spectral optical depths, aerosol size distributions, single-scattering albedo and complex index of refraction in the total atmospheric column[3] and also important in identifying the optical properties of aerosol biomass burning. There are also lidar networks such as The European Aerosol Research Lidar Network (EARLINET)[4] as well as others lidar sites scattered over the world that are important in the aerosol optical profiling studies. However, ground-based lidar observations cannot provide horizontal variability of the aerosols, for this cases there are a number of satellite remote sensors in orbit to provide a horizontal and global information about the aerosol distribution. Two important remote sensors in orbit of the globe are the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, designed with 36 spectral channels for a wide array of land, ocean and atmospheric investigation and has a unique ability

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to observe fires, smoke, and burn scars globally[5] and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), a satellite mission with the purpose of measuring the vertical structure and optical properties of aerosols and clouds and has been providing measurements since June 2006 that will improve our understanding of aerosol properties on global scale[6,7] as well an important instrument to the study the long-range aerosol transport.[8] According to IPCC 2007, the biomass burning is one of the most important sources of air pollution in the whole globe. In the last years there was a large number of studies concentrated in the physical and chemical properties of the burning biomass particles.[9–13] In that context Brazil has an important role in the biomass burning in South America scene[14,15] with detection of thousands of fire spots every year, most of these concentrated in the North, Mid-Western and Southern during the dry season (July-November)[16] and thus favoring the transport of aerosol plumes over large areas in the whole continent. We present in this paper an initial effort to map the aerosol biomass burning plumes transported from the North and Mid-Western into the Southeastern region in Brazil. In total 5 sites were chosen spanning from 9 to 23 South latitude and 46 to 67 West in longitude in coverage during 2007 and we were able to identify such transports principally during the months of August and September. In a first step of this study it has been developed a computational routine to map the CALIPSO overpasses over the whole country in order to retrieve the total coverage using as validation sites the brazilian portion of the AERONET sunphotometer sites in Rio Branco, Alta Floresta, Cuiabá, Campo Grande and São Paulo. These transports could be also validated by the sensors Acqua and Terra aboard MODIS. In a second stage we try to identify a possible biomass burning starting areas and track their transport trajectories as aerosol biomass burning (BB) plumes into the areas located at southeastern portion of Brazil, as the city of São Paulo where we are able to identify such plumes with an elastic backscatter lidar system. As the routine "flagged" that a long range biomass burning event occurred we listed the aerosol optical properties derived from the CALIOP instrument itself as the overpass-averaged profiles of the color ratio (1064/532 nm) nm and depolarization at 532 nm, the Aerosol Optical Depth (AOD) and Ångström Exponent (AE) from the sunphotometer retrievals at each specific site and lidar ratios (LR) - from CALIOP - which could be compared with the ground based lidar system in São Paulo. From the cases we have identified we have selected a period in the beginning of August 2007 as a case study that will be presented in Results and Discussions section of this paper.

2. INSTRUMENTATION

The backscatter Lidar system MSP Lidar, operating since 2001, has been set up in a suburban area in the city of São Paulo in the Center of Lasers and Applications at the Instituto de Pesquisas Energéticas e Nucleares. This system provides aerosol optical properties such as backscatter and extinction coefficients, extinction-to-backscatter ratio (Lidar ratio) and the aerosol optical thickness (AOT). The Lidar data are analyzed in synergy with the AOT values obtained from the AERONET network sun-tracking photometer in visible spectral region. The IPEN system is a coaxial mode single-wavelength backscatter pointed vertically to the zenith used to perform continuous measurements of suspended aerosols particles in the PBL.[17,18] It is based on the second and third harmonic frequencies of a commercial pulsed Nd:YAG laser with fundamental frequency at 1064 nm, which emits pulses of 100 mJ and 40 mJ output energy at 532 nm and 355 nm, respectively, with a repetition rate of 20 Hz. The optical receiver system consists of a Newtonian telescope of 300 mm of diameter with 1-2 mrad of field of view, narrow band interferences filters with $\sim$ 1 nm FWHM. A Hamamatsu R7400 PMT is used to detect the Lidar signal at 532 nm. The PMT output signal is digitalized and stored by a Lidar Transient Recorder LR 20-80/160 (LICEL-GmBh) which has a acquisition analog channel with 12 bit of resolution and 40 MHz. The data are averaged with a spatial resolution of tipicaly 15 to 30 m. The CALIPSO payload consists of three co-aligned nadir instruments designed to operate autonomously and continuously. A two-polarization Lidar system referred as Cloud and Aerosol Lidar with Orthogonal Polarization - CALIOP, a three-wavelength Imaging Infrared Radiometer - IIR, and a Wide Field Camera - WFC. The CALIOP laser transmitter subsystem consists of two identical lasers, each with a beam expander to reduce the divergence of the laser beam at the Earth's surface and a beam steering system that ensures the alignment between the transmitter and the receiver. These Nd:YAG lasers are diode-pumped and operate at 1064 nm and 532 nm with a pulse repetition rate of 20.25 Hz. Each laser produces 220 mJ output energy at 1064 nm, which is frequency-doubled to produce 110 mJ of energy at each of the two wavelengths. The lasers are Q-Switched to provide a pulse length of about 20 ns. The receiver subsystems measure the backscattering signal intensity at 1064 nm and the two orthogonal polarization components at 532 nm.[6] The Moderate resolution Imaging Spectrometer (MODIS) instrument flies on the Earth Observation System's (EOS) Terra and Aqua satellites. Both satellites are polar-orbiting, with Terra on a descending orbit (southward) over the equator about 10:30 local sun time, and Aqua on an ascending orbit (northward) over the equator about 13:30 local sun time. From a vantage about 700 km above the surface and a $\pm 55°$ view scan, each MODIS views the earth with a swath about 2330 km, thereby observing nearly the entire globe on a daily basis, and repeat orbits every 16 days. Each scan is 10 km along track. MODIS performs measurements in the solar to thermal infrared spectrum region from 0.41 to 14.235 m (Salomonson et al., 1989). The aerosol retrieval makes use of seven wavelength bands and a number of other bands to help with cloud and other screening procedures. To keep in line with common references in the aerosol literature, MODIS channels 1, 2, 3, 4, 5, 6 and 7 are known in this document as the 0.66, 0.86, 0.47, 0.55, 1.24, 1.64 and 2.12 μm channels, respectively.[5,19] The AERONET CIMEL aerosol measurements were performed to determine the AOT and Angström Exponent (AE) values at several wavelengths in the visible spectrum and thus to enable the assessment of the Aerosol Extinction values at the same spectral region.[17,20] The principle of operation of the CIMEL instrument is to acquire aureole and sky radiances measurements. The standard measurements are taken 15 min apart, in order to allow for cloud contamination checking.[2]

3. METHODOLOGY

In order to obtain the CALIPSO and MODIS satellites overpasses in specifc areas in North, mid-western and southeastern region of Brazil a computational routine in the Mathematica 6.0®program has been written. We present here the satellite tracking over Brazil. The satellite completes 14.55 orbits per day with a separation of 24.7° longitude between each successive orbit at the equator and progresses westward 10.8° on succeeding days producing a 16-day period as a uniform WRS grid over the globe[21] and should cover the entire country of Brazil in 16 days as well. As it can be seen Figure 1 bears a 6-day bundle of trajectories spanning from west to east from August 02 until August 09, 2007. Also in this plot we display the location of the 5 sites used in our current study and their location details are given in Table 1.

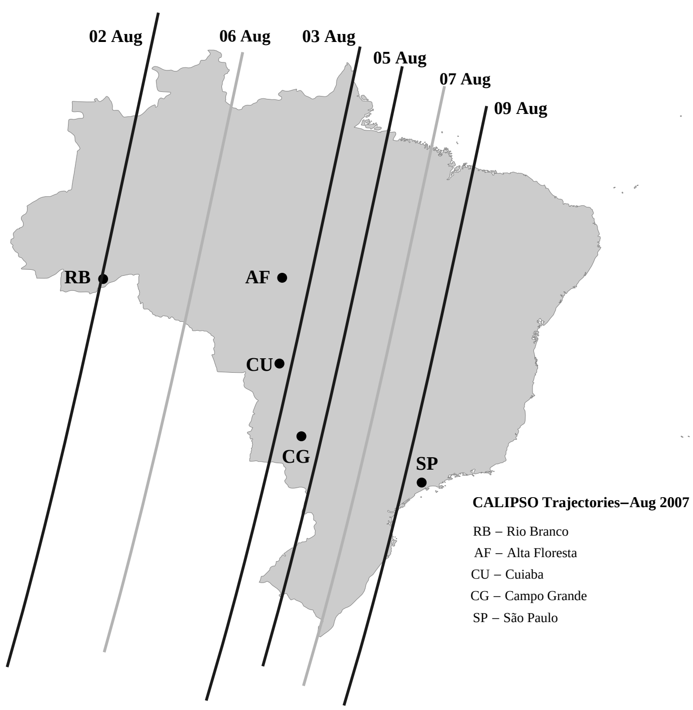


Figure 1. CALIPSO ground tracking over Brazil from August 02 until August 09 2007. The black trajectories were used in our study as they comply with the requisite of being at least 300 km from a site while the gray ones do not.

Table 1. Table of geographical position of the 5 sites in this study, their type as (S)source or (Sk)sink of biomass burning transported plumes, and ground based intruments as (A)Aeronet and/or (L) lidar.

Site	LON,LAT	Altitude (m)	Type of Site	Closest Distance (km)
Rio Branco (RB)	09°98" S, 67° 82" W	153	A,S	12
Alta Floresta (AF)	09°09" S, 55° 91" W	283	A,S	203
Cuiabá (CB)	15°61" S, 56° 09" W	165	A,Sk	86
Campo Grande (CG)	20°45" S, 54° 63" W	592	A,Sk	137
São Paulo (SP)	23°33" S, 46° 44" W	840	A,L,Sk	132

To verify if a long range transport of biomass burning plume occurred we developed a strategy (algorithm) as depicted in Figure 2. As the objective in this work is monitoring the transport of aerosol biomass burning layers from regions where there is a culture of burning vegetation for deforestation purposes we have selected as starting points the sites *RB* and *AF*, as potential sources of biomass burning aerosols which could be brought towards the other 3 (Sk) sink sites, namely *CB, CG* and *SP*. As each site had an AERONET sunphotometer we have put a criterion in which based on the median values of the AOD and AE, when these two quantities were exceeded we had an *"Y"* flag to qualify as the possible presence of biomass burning plumes in the site. In general, it meant that when both events of higher values of AOD were present meaning a high level of extinction in conjunction with high values of AE, indicating the predominance of small sized aerosols, typical for smoke plumes. As each site signalled the Y flag we would jump to the next site and check the photometer parameters but within a date window of 3 days ahead of the day when the event happened at the previous site, thus allowing the transported plume to arrive at the site being inspected. If at any site before reaching the SP site an N flag occurred the whole procedure would be reinitialized at the original sites (RB and AF) but in the next day and so on until the end the year 2007 was reached. When all site flagged Y down to the SP site, a long range transport as well the sunphotometer aerosol optical property dataset for each site would be recorded.

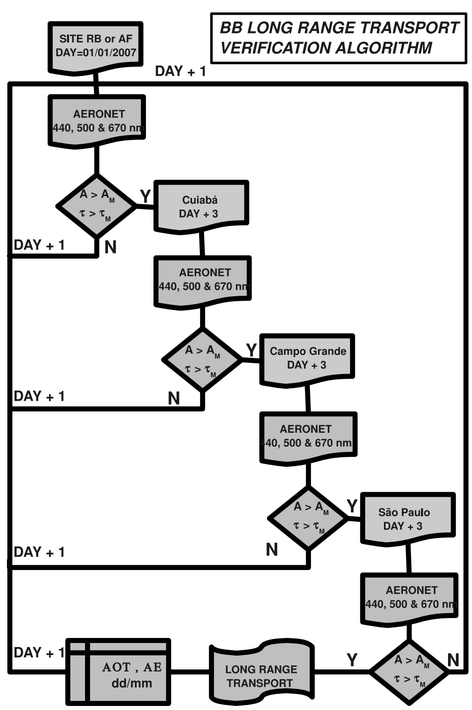


Figure 2. CALIPSO ground tracking over the globe for a whole covered day for 07 October 2007.

The next step in our procedure after the record of a biomass burning event is to cross-check if we had a CALIPSO overpass over all sites within the time period recorded by the forementioned algorithm and in which the farthest distance would not be over 300 km from each site. Once this was achieved we selected the transported biomass burning day "window" we again retrieved all CALIPSO related information for each that would fit into the closest distance criterion and obtained a 300 single-shot profile, in a way that 150 singles-shot would lie north of the inspected site and the other 150 shots South of it.[8] Once this action was performed we obtained the averaged profiles for the total attenuated backscatter (at 532 nm and 1064 nm), the perpendicular attenuated backscatter (532 nm), the color ratio, the depolarization ratio and lidar ratio. The CALIPSO level 1.0 dataset was employed for all quantities mentioned except the latter, namely the lidar ratio, which was retrieved from level 2.0 instead. After this we have selected specific days from MODIS to complete our comparison and finally the HYSPLIT back and forward trajectories at the www.arl.noaa.gov/HYSPLIT.php site.

4. RESULTS AND DISCUSSIONS

From the selected events with biomass burning plumes being transported in coincidence with CALIPSO, we have obtained 8 cases, 4 in August/2007 and 4 in September/2007, that were within 300 km range from each site. We will show here only the event corresponding to the August 2 - 9 period and the others should be shown in the near future. From the sunphotometer we have obtained the AOD and AE values for all sites and we show the ones obtained for the RB site and its scatter plot is shown in Figure 3. In this plot the AE values below the horizontal line corresponding to the median, $\overline{AE} = 1.61(13)$ are an indication that most of the aerosols load is in the coarse mode size distribution, while the opposite applies to those values above the median line, and therefore in the fine mode sized type of aerosols. In the same fashion we employ the same reasoning to the AOD median vertical line, $\overline{AOT} = 0.160(79)$ corresponding to low/high extinction (absorption) of radiation if lying left/right of the diving line. Summarizing we have split the plot in four distinctive regions and for this study should be regarding those days on the rightmost/upper sector of this plot marked with a ★ sign, as a strong indication of the presence of predominantly biomass burning aerosols in the atmosphere. As we selected those ★ type of events with CALIPSO overpasses we have found a case in which the Biomass Burning Long Range Transported Verification Algorithm flagged "Y" for all sites in August 2 to RB, August 3 to AF and CB, and August 3 and 5 to CG and August 9 to SP.

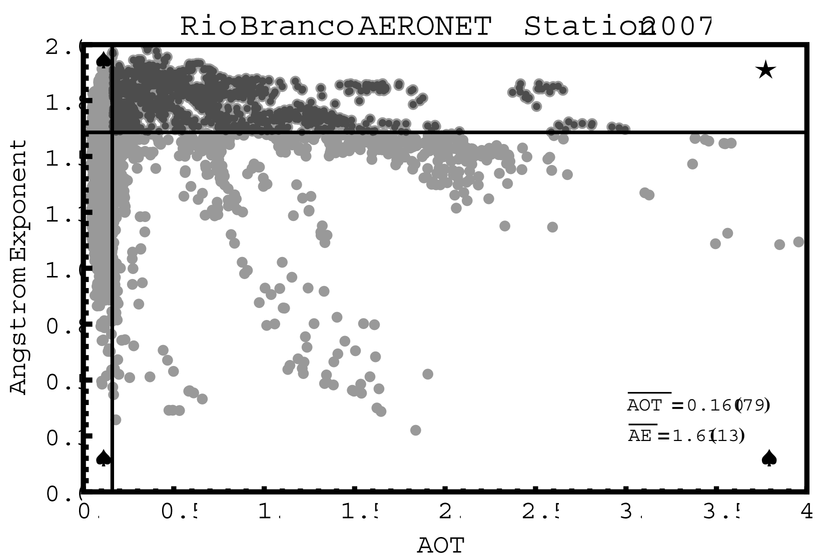
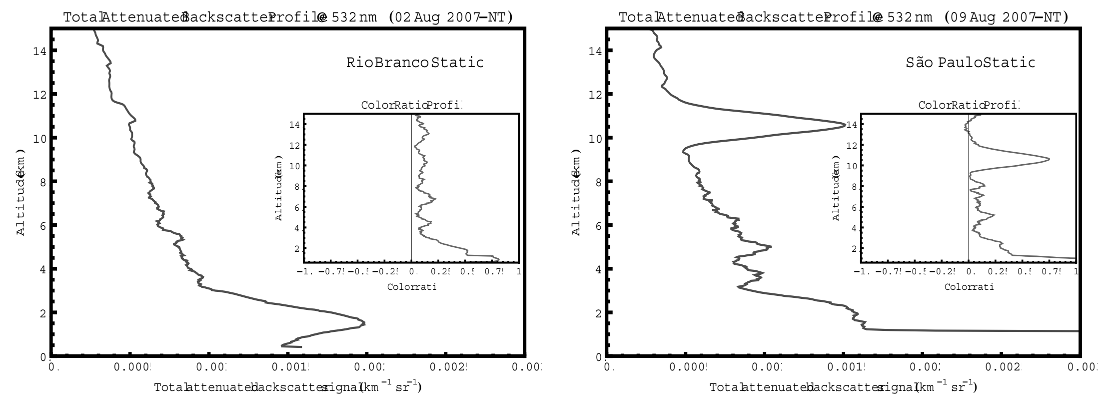


Figure 3. Angström Exponent versus AOT values for Rio Branco Station on 2007. The region marked with the ★ sign represents values of AE and AOT greater than the median of the respective variables given in the plot.

Once these dates were selected we have obtained the CALIPSO dataset for the time period in which we believed the transport occurred along the 5 sites and retrieved the total attenuated backscatter at 532 nm and 1064 nm, depolarization ratio, color ratio and lidar ratio. The 300-single-shot averaged profiles were also averaged between 0 and 6 km and given in Table 2. In figures 4(a) and 4(b) are those for the RB and SP sites and provides information about the attenuated backscatter and color ration (inset). These averaged profiles are displayed as a 20-moving-averaged smoothed curves. The RB color ratio profile shows a varying pattern up to the top of the boundary layer as it displays a less alternating behavior above the BL. However there are two small peaks at around 5 and 7 km indicating some layers of a distinctive of aerosols. The same feature can be also observed at the SP site and a peak around 5 km which was confirmed by ground based observation with the ground-based lidar system at this site.



(a) CALIPSO total attenuated backscatter profile @ 532 nm and its Color Ratio profile for 02 August 2007 in the nighttime for Rio Branco station

(b) CALIPSO total attenuated backscatter profile @ 532 nm and its Color Ratio profile for 09 August 2007 in the nighttime for Sao Paulo station

Figure 4. CALIPSO obtained quantities at the RB and SP sites.

In Table 2 we summarize the optical quantities found by all plataforms: the AERONET Sunphotometer's ($\overline{AOT}$ and $\overline{AE}$), CALIPSO's ($\overline{\beta}$, $\overline{\delta}$ and $\overline{LR}$) and $\overline{LR}*$ from the MSP-Lidar System. The AOT values found with the sunphotometer are close related to those presented by MODIS as well.

Table 2. Mean values of atmospheric optical components retrieved from AERONET Sunphotometer, CALIPSO Satellite and MSP-Lidar System

Site	$\overline{AOT}$	$\overline{AE}$	$\overline{\beta}$	$\overline{\delta}$	$\overline{LR}$	$\overline{LR}*$
Rio Branco (RB)- Aug 02	0.160 (79)	1.61 (13)	0.0012 (4)	0.012 (24)	70 (21)	–
Alta Floresta (AF)- Aug 03	0.130 (52)	1.22 (30)	0.0014 (5)	0.026 (31)	69 (21)	–
Cuiabá (CB)- Aug 03	0.118 (36)	1.29 (17)	0.0073 (4)	0.057 (88)	70 (21)	–
Campo Grande (CG)- Aug 03	0.19 (28)	1.45 (30)	0.0073 (31)	0.025 (85)	69 (21)	–
Campo Grande (CG)- Aug 05	0.19 (28)	1.45 (30)	0.0012 (3)	0.043 (67)	70 (21)	–
São Paulo (SP)- Aug 09	0.198 (78)	1.46 (9)	0.0013 (15)	0.047 (73)	70 (21)	75 (22)

The mean values of $\overline{\beta}$, $\overline{\delta}$ and $\overline{LR}$ are, as mentioned before, calculated within 0 and 6 km. The $\overline{\beta}$ given in each site which are greater than $0.0010 km^{-1} sr^{-1}$ are a strong indication of land surface type aerosol,[22,23] besides the Depolarization $\overline{\delta}$ values are all less than 0.075 and greater than 0.0005, at this time indicating that biomass burning type of aerosol are present, and the average lidar ratio $\overline{LR} = 70(21) sr$ also supports this claim. It is worth mentioning that despite SP site be a typical urban site the same type of aerosol was also identified by the LR retrieval with the ground-based lidar system, $\overline{LR}* = 75(22)$ sr. By consulting the MODIS site (http://modis-atmos.gsfc.nasa.gov/) we could as well identify many hotspots due burnings in the area of Brazil on August 03 and 05. Figure 5 shows the HYSPLIT forward trajectories 80 hours after starting at the two source sites RB and AF. The trajectories start at diferent altitute levels (4000 m, 4200 m and 4500 m AGL) and move towards the Southeastern part of Brazil. Despite originating at sites that are about 2000 km apart, their trajectories will cross one another in the border between Brazil and Paraguay where the air masses will probably mix and move towards the last site, SP. On the other hand the CG and CB sites are mainly influenced by the air parcel coming from the AF site. This somehow could be validated by the values given in Table 2.

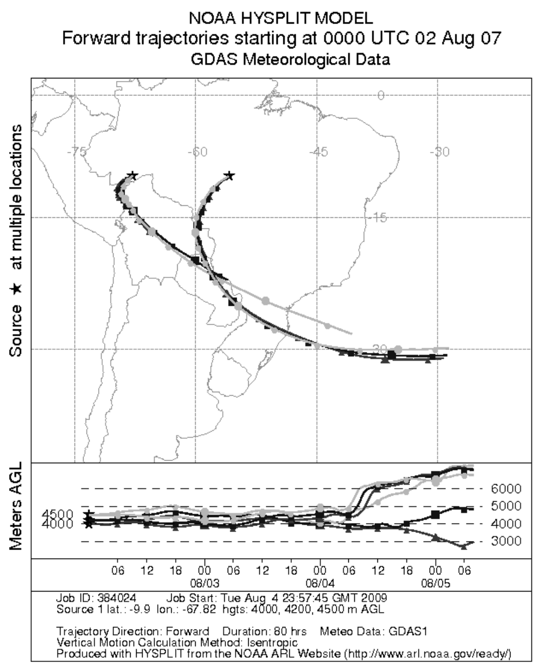


Figure 5. HYSPLIT generated forward trajectories inialized on August 03 at the RB and AF and going southeast towards the Sink sites (CG, CB and SP).

5. CONCLUSIONS

In this paper we have presented an initial effort to map the aerosol biomass burning plumes transported from the North and Mid-Western into the Southeastern region in Brazil. It has been developed a computational routine to map the CALIPSO overpasses over the whole country and retrieved optical parameters of 5 AERONET sunphotometer sites. From the selected events with biomass burning plumes being transported in coincidence with CALIPSO using the BB Long Range Transport Verification Algorithm, we have obtained 8 cases, 4 in August/2007 and 4 in September/2007, that were within 300 km range from each site. We have analyzed one single event in August 02 - 09 period and the AOT and AE values retrieved from the sunphotometer indicated that the most aerosol loaded in all the sites corresponding to the biomass burning aerosol particule. That hypothesis has been validated by the mean values of $\overline{\beta}$, $\overline{\delta}$ and $\overline{LR}$ about 70 sr for all sites retrieved from the CALIPSO measurements. Finally the HYSPLIT forward trajectories showed that the air masses loaded by biomass burning aerosol particule was transported from RB and AF sites and reached the last site in SP.

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