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Relationship between Amazon biomass burning aerosols and rainfall over La Plata Basin

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Abstract

High aerosol loads are discharged into the atmosphere by biomass burning in Amazon and Central Brazil during the dry season. These particles can interact with clouds as cloud condensation nuclei (CCN) changing cloud microphysics and radiative properties and, thereby, affecting the radiative budget of the region. Furthermore, the biomass burning aerosols can be transported by the low level jet (LLJ) to La Plata Basin where many mesoscale convective systems (MCS) are observed during spring and summer. This work proposes to investigate whether the aerosols from biomass burning may affect the MCS in terms of rainfall over La Plata Basin during spring. Since the aerosol effect is very difficult to isolate because convective clouds are very sensitive to small environment disturbances, detailed analyses using different techniques are used. The binplot, 2D histograms and combined empirical orthogonal function (EOF) methods are used to separate certain environment conditions with the possible effects of aerosol loading. Reanalysis 2, TRMM-3B42 and AERONET data are used from 1999 up to 2012 during September-December. The results show that there are two patterns associated to rainfall-aerosol interaction in La Plata Basin: one in which the dynamic conditions are more important than aerosols to generate rain; and a second one where the aerosol particles have a role in rain formation, acting mainly to suppress rainfall over La Plata Basin.

1 Introduction

During the dry season in Amazon and Central Brazil there is high concentration of aerosol particles from biomass burning associated with human activities, mainly agriculture and deforestation (Artaxo et al., 2002; Freitas et al., 2005; Martins et al., 2009). These aerosols can act as CCN (cloud condensation nuclei), potentially changing the cloud microphysics, as well as the radiative properties and lifetime of clouds (Martins et al., 2009) affecting Amazon's radiative budget (Lin et al., 2006).

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It is well-known that aerosols can affect the environment through scattering and absorption of solar radiation (direct effect) and interactions with clouds (indirect effect). The Intergovernmental Panel on Climate Change (IPCC, 2007) indicates that the uncertainty in aerosol effects on clouds is large compared to other forcings due to human activities. High concentrations of aerosol can modify cloud droplet distribution, can increase droplet concentration, while keeping a constant liquid water content (Twomey, 1974). The reduction of cloud droplet size changes the precipitation efficiency and causes an increase of liquid water content and lifetime of the clouds (Albrecht, 1989).

Comparing polluted and clear atmospheres, Rosenfeld (1999) observed that high concentrations of aerosol suppress precipitation and that clouds present colder tops than in clear conditions. Through numerical modeling, van den Heever et al. (2006) observed that an increase of aerosol concentration causes an increase of updraft velocity due to latent heat release by condensation. They verify an increase in amounts of rain associated to an increase of GCC (Giant Cloud Condensation Nuclei) and IFN (Ice-Forming Nuclei) whereas an increase of CCN concentration causes a rainfall decrease. High CCN concentrations can also increase ice particles number (van den Heever et al., 2006) and, thereby, lighting (Albrecht et al., 2011). In the Amazon Basin, Andreae et al. (2004) indicate that cloud formed in regions with heavy load of biomass burning aerosols have droplet spectra with different properties than clouds formed in clear environments.

Convective clouds are very sensitive to small environment differences; therefore, it is very difficult to isolate the aerosol effect (Wall, 2013). According to Khain et al. (2008) the precipitation can be affected by drop condensation and ice deposition (generation) and drop evaporation and ice sublimation (loss), where these variables are perturbed by wind shear, moisture, instability, aerosol, etc. However, it seems that the atmospheric conditions are more important than aerosol for rainfall production (Jones and Christopher, 2010).

Fan et al. (2007) found that rain delay is more sensitive to relative humidity than to aerosol and only under conditions of significant moisture the aerosol can change

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substantially the convection and rain rate. Numerical studies about isolated deep convective clouds provided by Fan et al. (2009) show that in case of strong wind shear, generally, aerosols suppress convection. This effect is greater in humid air than dry air. Fan et al. (2009) also observed an enhancement on convection by increasing aerosol under weak wind shear, until an optimum aerosol concentration is reached.

Here the sensitivity of rainfall to aerosol is examined for the La Plata Basin which is the fifth largest hydrographic basin in the world and the second largest in the continent, covering Uruguay, Brazil, Argentina, Paraguay and Bolivia. It has a very large hydroelectric potential with several plants placed on its rivers. Located on one of most densely populated regions in South America, the La Plata Basin sustains domestic consumption and agricultural activities and, thereby, represents an important economic factor for the region.

Fig. 1 from Silva Dias et al. (2009) (c.f. Durkee and Mote, 2010) shows the geographical and seasonal distribution of Mesoscale Convective Systems (MCS) in South America. It may be seen that there is greater number of Mesoscale Convective Systems (MCS) during austral spring and summer over South America, mainly over Paraguay, Northern Argentina and Southern Brazil. These systems are large Cumulunimbus clusters with lifecycle from hours to days and can cause floods, heavy rainfall and severe weather (Velasco and Fritsch, 1987; Fritsch and Forbes, 2001). Zipser et al. (2006) reports that in the La Plata Basin the MCSs are seen as the most intense in the world.

Observational studies from Marengo et al. (2002) and Salio et al. (2007) show a narrow flow over north of La Plata Basin and east of Andes with a maximum wind speed around 2000 m of altitude, called Low Level Jet (LLJ). The LLJ is responsible for carrying large heat and moisture contents from the Amazon Basin southward toward the La Plata Basin, feeding the convective systems that develop in the region. Furthermore, Freitas et al. (2005) suggest that the LLJs can transport aerosol from biomass burning in Amazon and Central Brazil to La Plata Basin in the dry season which corresponds to austral winter and spring. Thus, on austral spring, the MCSs develop under high aerosol loading conditions and, consequently, may be affected by these particles.

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Figure 2 is a schematic illustration about the present work context. The climatologies for Aerosol Optical Depth (AOD) at 440 nm for Rio Branco and Alta Floresta stations and rainfall for Asunción, Santa Maria and Buenos Aires are shown. The AOD and rainfall are retrieved by AERONET and TRMM-3B42, respectively. Ji Paraná, Cuiabá, Santa Cruz and Campo Grande (in red) are also AOD stations, their climatological graphics are not shown in Fig. 2 but their data are used in this study. AOD stations show high values between July and December (dry season) with peaks, in September, about 1.0 for Rio Branco and 1.5 for Alta Floresta. These high values are due to biomass burning activity (Artaxo et al., 2002) and, eventually, are transported via LLJ to La Plata Basin (Freitas et al., 2005). Significant amounts of rain are observed in most of the year for Asunción (less in July-September) and whole year for Buenos Aires and Santa Maria. Indeed, the aerosols from biomass burning region may potentially affect the hydrologic balance of La Plata Basin. However the question that arises is, if aerosols from biomass burning in the Amazon and Central Brazil affect the evolution of MCS in the La Plata Basin, how much would that be in terms of precipitation? This work proposes to address this question using available data from the AERONET,TRMM-3B42 and the NCAR/DOE reanalysis. Section 2 describes the data and method of analysis; in Sect. 3 a case study is presented to illustrate the large scale setup of a typical MCS in the region. Section 4 presents the results and discussion of the available time series and conclusions are presented in Sect. 5.

2 Data and methods

Three different methods will be presented in an attempt to observe the aerosol effects on rainfall over La Plata Basin. As described below, this study uses reanalysis to characterize the dynamic and thermodynamic environment, precipitation estimates from satellite and Aerosol Optical Depth (AOD) data. The data period extends from 1999 to 2012 and the focus is the dry season and beginning of the wet season lasting from September through December.

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2.1 Reanalysis 2

Reanalysis 2 data from NCEP-DOE (National Center for Environmental Prediction – Department of Energy) is used in order to provide large scale information over La Plata Basin. This data is an updated version of NCEP-NCAR (National Center for Atmospheric Research) reanalysis with improvements to forecast model and data assimilation system (Kanamitsu et al., 2002). It has an updated 6-hourly global analysis series from 1979–present and 2.5°x2.5° grid spacing and is available from http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html. Winds at 850 hPa are used to define the circulation associates with convective systems. The field of vertical p-velocity ω at 500 hPa is used to indicate the dynamic forcing with negative ω indicating upward vertical motion favoring the development of clouds while positive ω indicates subsidence in principle inhibiting clouds. The mean relative humidity between 700 and 500 hPa (RH) has been chosen as an indicator of mid level moisture in the environment.

2.2 TRMM-3B42

The spatial and time variations of rainfall have been obtained from TRMM (Tropical Rainfall Measuring Mission) satellite, generated by the 3B42 algorithm version 7. These gridded rainfall estimates are available from 1998-present with a 3-h temporal resolution and 0.25° × 0.25° spatial resolution covering global latitudes from 50° S to 50° N (http://trmm.gsfc.nasa.gov/3b42.html). Rainfall rate (RR) in mm day^{-1} and the percentage of rainy grid points over the blue-rectangle (rainfall fraction) were computed. A rainy grid point is defined when RR $>$ 0.2 mm hr^{-1}.

2.3 AERONET

AOD data provided by AERONET (Aerosol Robotic Network), coordinated by NASA (National Aeronautic Spatial Agency), have been used. AERONET is a global network of sunphotometers that has monitored AOD and aerosol optical properties since 1993. The optical depth of aerosols indicates the aerosol concentration in the atmospheric column. The level 2 product of AOD for the wavelength of 440 nm has been used for the sunphotometers at Alta Floresta, Ji Paraná, Rio Branco, Santa Cruz, Campo Grande and Cuiabá-Miranda. These locations are indicated in Fig. 2.

2.4 Filtering

The main assumption of this work is that aerosol from biomass burning is advected from Amazon and Central Brazil to La Plata Basin under north wind conditions (Freitas et al., 2005). Figure 3 shows the average wind field for of all north wind cases from 1999 to 2012 in the dry to wet season; the blue box represents the interest region in the La Plata Basin where rainfall and aerosol relationships are investigated. The red box indicates a broad region where the biomass burning aerosol is originated. All cases where the wind at 850 hPa is from the north were used to investigate the rainfall and AOD relationship. It is considered as north wind case when the average meridional wind component over the red and blue rectangles is negative in both. The wind direction between 30° and 90° is discarded avoiding sample contamination from others aerosol sources.

The rainfall rate RR, the vertical p-velocity ω, and the average relative humidity RH have been averaged over all grid points in the blue rectangle. Also, an average of RR over the red rectangle has been used to define days where rainfall is minimal over the region where the aerosol travels in its path toward the south. Days when averaged RR over the red rectangle was below 3 mm day^{-1} were kept while the rest of the days were eliminated to avoid including cases where aerosols would be removed by precipitation during their path from the origin until their destination in the blue rectangle.

The aerosol travel time from the origin until the destination has been taken into account by defining a time lag as the time (in days) that aerosols take to arrive at the La Plata Basin. The rain event is defined as average RR > 1 mm day^{-1} over the blue rectangle. The time lags considered were from 1 up to 5 days. For each rain event the time

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lags were considered getting a date when the AOD may be retrieved by AERONET stations as the origin for the aerosols that reach La Plata Basin. Thus, the AOD and rainfall time series can be correlated for each time lag. The best correlation was taken as an indication of the optimal time interval. Also, the time lag was calculated based on mean wind at 850 hPa and distance between the origin and destination. The results were similar with the previous time lag method and then it was decided to use the correlation time lag method.

In order to simplify the nomenclature of average RR, average RH (mean 700-500 hPa) and average ω (500 hPa) from blue rectangle, they will be called just RR, RH, and ω, respectively.

2.5 Bin plot

Binplot is an easy tool to explore the effect of low and high aerosol loadings on the rainfall. This method consists, basically, in averaging rainfall rate between a bin range of AOD that, in this case, was 0.1. Then for each AOD range the average rainfall rate was calculated and plotted for each of the AERONET stations.

2.6 2D histograms

This method is similar to the binplot but now, besides AOD intervals, intervals of ω and rainfall fraction will be considered. The rainfall fraction is defined as the percentage of grid points with RR > 0.2 mm h^{-1}. For each interval of ω, representing a given dynamic pattern, the aerosol effect is investigated.

2.7 Combined EOF

According to methodology contained in Wilks (2006), the combined Empirical Orthogonal Functions (EOF) has been used to determine patterns in the joint variation of AOD, rainfall rate, ω and relative humidity. This proceeding has been used as another way to

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detect aerosol effects with similar synoptic patterns. Then EOF calculation was divided in 4 steps:

1. A matrix of data was built as

$$\begin{bmatrix} \mathrm{AOD}_1 & \mathrm{RR}_1 & \omega_1 & \mathrm{RH}_1 \\ \mathrm{AOD}_2 & \mathrm{RR}_2 & \omega_2 & \mathrm{RH}_2 \\ \vdots & \vdots & \vdots & \vdots \\ \mathrm{AOD}_n & \mathrm{ARR}_n & \omega_n & \mathrm{RH}_n \end{bmatrix}$$

   where, n corresponds to the number of cases selected;

2. The matrix was normalized by subtracting each column by its average and dividing by its standard deviation;

3. The covariance matrix was determined from the normalized matrix;

4. The combined EOF was calculated through the eigen function from R software (http://www.r-project.org) that uses the LAPACK (Linear Algebra PACKage) routines.

The results from the statistical analysis described above will be presented after an overall presentation of a case study where the general features associated to mesoscale convective systems in the La Plata Basin will be presented.

3 A case study

A Mesoscale Convective System (MCS was observed in 12 September 2007 and will be used to illustrate the motivation of this work. Figure 4 shows the AOD for September 2007 for each station in the Amazon and Central Brazil. High AOD values are associated with intense biomass burning (Artaxo et al., 2002) with peaks around 5 for Alta

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Floresta, 4 for Ji Paraná, 3 for Rio Branco and 2 for other stations (Santa Cruz had no measurements on this month). Looking for days closer to September 12th, it is possible to observe AOD values over 2 for all stations. Then on September 12th winds from the North indicate a case of transport of high aerosol loadings from Amazon and Central Brazil to the south. This condition provides an environment with high aerosol concentration where the MCS was formed.

Satellite images are shown in Fig. 5 for 05:00, 06:45, 10:15 and 14:00 UTC revealing the formation of MCS up to the mature stage. For the first hours some isolated cells are formed and begin to grow and organize, originating a large cloud cluster over northeast of Argentina and reaching the mature stage about 14:45 UTC. This system reached brightness temperatures below −70°C and, according to the precipitation estimative from TRMM-3B42, generated 6 mm day^{-1} area average and a maximum of 14.4 mm/h, both over the blue rectangle.

Wind and relative humidity at 850 hPa, mean 700-500 hPa RH (shaded) and ω at 500 hPa (contour), and wind and divergence at 200 hPa are presented in Fig. 6. Looking at Fig. 6b, a moisture region with RH above 50 % is apparent, slightly to the east from a moisture flow observed at 850 hPa (Fig. 6a). The ω field is close to zero over MCS location, in other words, neutral condition at 500 hPa. The moisture flow from the North is apparent along with a wind convergence at low levels and upper level divergence at 200 hPa. This condition favors convection as discussed by Salio et al. (2007). The question posed is whether systems like this may have been affected by aerosols coming from the North and intruding in low to mid levels into the MCS. Next section will investigated if the aerosols may cause any detectable effect on precipitation over La Plata Basin, thus influencing in hydrology of the region.

4 Results and discussion

Comparisons between aerosols and rainfall have been made by considering the better correlated time lag between the path from biomass burning region to La Plata Basin as described in Sect. 2.4. Figure 7 shows the rainfall rate as a function of AOD. It can be seen that rainfall decreases as AOD increases, that is, higher aerosol load is associated with lower precipitation. This pattern occurs in all stations and it is more significant for AOD below 1, but is it really related to aerosol loads? Or may it occur due to another forcing?

Dynamics is one of most important forcings to generate rain and, for this reason, it is very difficult to recognize the aerosol effect that is usually secondary. In this context, dynamic patterns were separated using the two-dimensional histograms. The average rainfall rate (shaded boxes) as a function of rainfall fraction and AOD is shown in Fig. 8. Differences between rainfall fractions are immediately apparent. Below 40 % there is no contrast among the shaded boxes, in other words, it is not possible to detect the aerosol effect. For values above 40 %, strong contrast among the boxes can be seen, indicating a possible role of aerosols on rainfall. However, patterns cannot be clearly identified, probably, because there are other forcings that are dominant.

Figure 9 shows the average rainfall rate as a function of ω at 500 hPa and AOD. Differences between strong and weak ω (below and above $-2.5\,\mathrm{Pa\,s^{-1}}$, respectively) are easily observed for all stations. AOD dominates the precipitation for low omega values and, in contrast, the vertical velocity dominates the precipitation under high ω values. Thus, aerosol effects dominate under week dynamic forcing conditions inhibiting rainfall.

In another attempt to observe the aerosol effect and reinforce the previous results, combined EOF was calculated. Table 1 shows the variance explained by the first and second eigenvectors and the total explained by these two. The first EOF explains around 43 % of the variance of the dataset for all AOD stations and the second EOF 31 %, together this eigenvectors represent more than 70 % of the data variance explained. The other two EOFs are not shown since they explain lower portion of the variance.

EOFs and their respective components (AOD, RR, ω, RH) are shown in Table 2 as values indicating perturbations around the average. Looking at e_1 for Alta Floresta

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station it is possible to verify that this eigenvector detected a pattern with average AOD (close to zero perturbation), and below average RR, above average ω and below average RH, representing a pattern. One important thing about EOFs is that they can be analyzed also in the negative pattern, then e_1 also detected average AOD, and above average RR, enhanced negative ω and above average RH. The interpretation of this result is that when we have AOD near average, low (high) values of rainfall rate convection and a dry (moist) atmosphere, occur under favorable (unfavorable) conditions as defined by upward (downward) large scale motion. This pattern found in e_1 is seen in all stations and may be associated with dynamic forcing of rainfall.

The e_2 pattern for Alta Floresta present high (low) AOD, low (high) RR, and close to average ω and above (below) average RH value, it means high (low) aerosol loads are associated with rainfall below (above) of average. The pattern is the same for all stations and indicates that e_2 detected the aerosol forcing, associated with rain suppression. These results agree with the two-dimensional histograms shown before and with Jones and Christopher (2010). Jones and Christopher (2010) have used EOFs to identify possible interactions between aerosols and precipitation in the Amazon Basin. e_1 calculated by these authors identify atmospheric conditions favourable for rainfall and e_2 detected the aerosol forcing associated with low-level stability causing rainfall inhibition, may be representing the semi-direct effect of aerosols.

5 Conclusions

Based on previous work (Freitas et al., 2005) that indicates the aerosol can be transported by the LLJ from Amazon and Central Brazil biomass burning regions to La Plata Basin, this work used three statistical tools in attempt to isolate the aerosol effect from biomass burning on rainfall over La Plata Basin. The period analyzed was 1999–2012 during the dry season and beginning of the wet season (September–December) using data from AERONET, TRMM-3B42 and reanalysis 2.

Generally, the results show that high aerosol concentration tends to suppress precipitation for the three statistic methods used. It was only possible to detect the aerosol effect on rainfall fractions above 40 %, through 2-D histograms. When absolute values of ω are large, aerosol effects are not detected. However for $\omega < -2.5\,\mathrm{Pa\,s^{-1}}$ (weak dynamic forcing), high aerosol concentration tends to suppress rainfall.

The two first patterns detected by the EOF analysis explain together more than 70 % of the data variance, corresponding to about 43 % for the first EOF and 31 % for the second one. The first eigenvector identified the dynamic forcing in which strong vertical velocities represented by ω, moist atmosphere at medium levels and aerosol concentration near average cause rain above of average. e_2 detected the aerosol forcing which high aerosol loadings in a slightly moist atmosphere with ω below average tend to suppress rainfall. These results show that the dynamic component is the main forcing for rain production, while aerosols have a role inhibiting the rainfall under weak large scale forcing.

The mechanism of rain suppression in MCS by aerosol is certainly a very complex one. Simpler cases of warm rain suppression by aerosol and of single cloud rainfall effects due to aerosol indicate possible processes to take into account. However, the dynamics of large MCS involve multiscale interactions, from cloudscale to mesoscale to large-scale, over a period of several hours. In the particular case of the MCS over La Plata Basin the scale interaction is apparently affected by the cloud microphysics interaction with a steady flow of aerosol coming from biomass burning regions to the north. The results reported here indicate a relationship that needs further investigation using numerical techniques.

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Table 1. Variance explained from first and second EOFs and both together for each AOD station.

	R_1^2 (%)	R_2^2 (%)	$R_1^2 + R_2^2$
Alta Floresta	41	31	72
Ji Paraná	43	30	73
Rio Branco	42	34	76
Santa Cruz	45	30	75
Campo Grande	41	31	72
Cuiabá	43	30	73

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Table 2. EOFs and their components for each AOD station.

Stations	EOF	AOD	RR	ω	RH
Alta Floresta	e_1	0.0	−0.5	0.7	−0.6
	e_2	0.8	−0.6	−0.1	0.3
Ji Paraná	e_1	−0.2	0.7	−0.5	0.5
	e_2	0.8	−0.1	−0.5	0.2
Rio Branco	e_1	0.3	0.2	−0.7	0.6
	e_2	0.6	−0.7	0.2	0.2
Santa Cruz	e_1	0.1	0.5	−0.7	0.6
	e_2	0.9	−0.5	−0.2	0.0
Campo Grande	e_1	−0.1	0.5	−0.7	0.5
	e_2	0.8	−0.5	−0.2	0.4
Cuiabá	e_1	0.0	0.6	−0.6	0.5
	e_2	0.9	−0.3	−0.3	0.2

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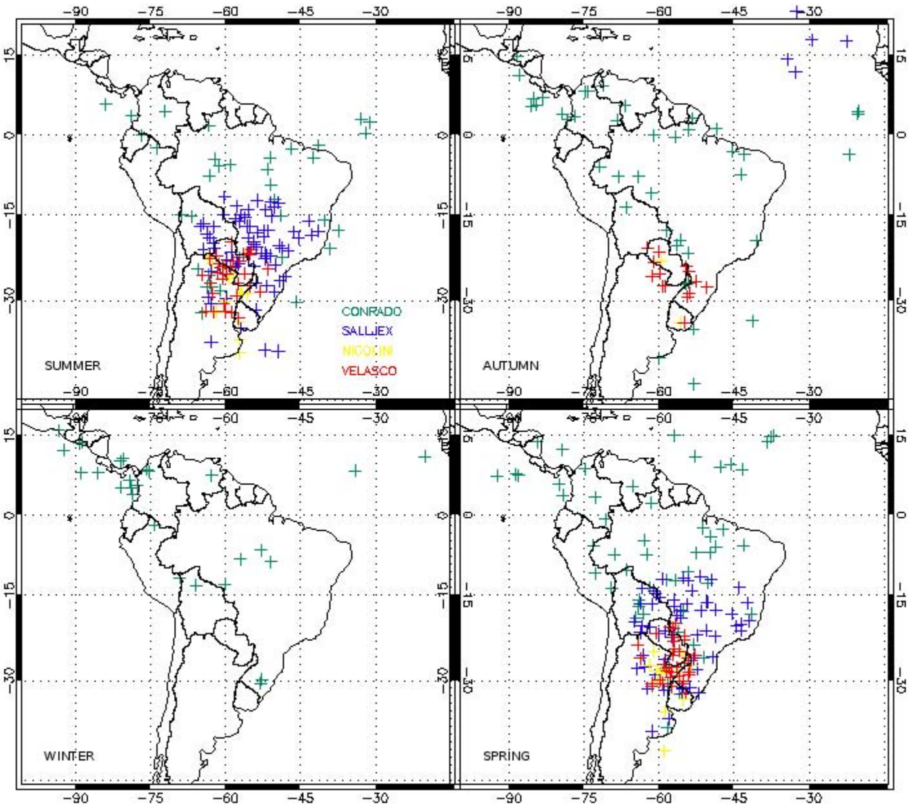

Fig. 1. Climatological distribution of MCSs over South America for each season (Silva Dias et al., 2009). The figure is a compilation of results from Velasco and Fritsch (1987), Conforte (1997), Torres and Nicolini (2002), Salio et al. (2007). The MCSs observed during SALLJEX (Vera et al., 2006) are indicated.

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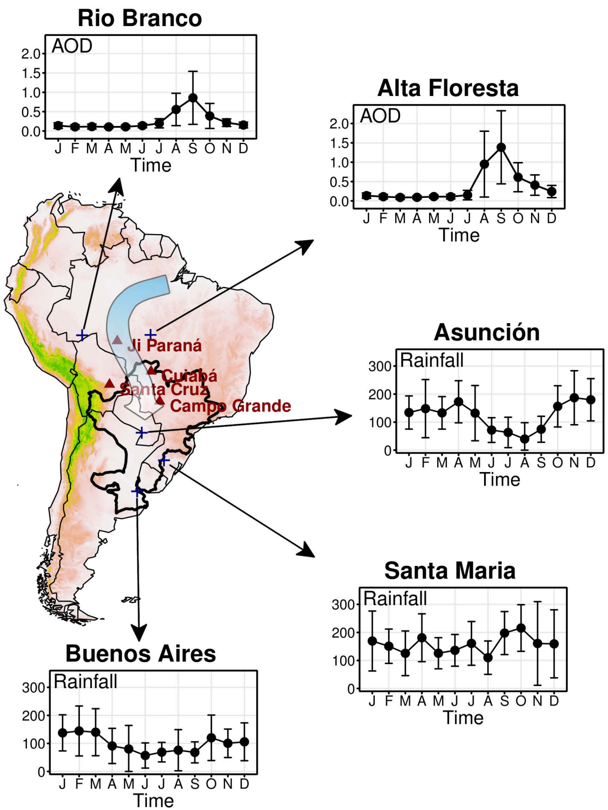

Fig. 2. Schematic illustration about this work context. The graphics are climatologies of AOD for Rio Branco and Alta Floresta AERONET stations, and rainfall estimative from TRMM-3B42 for Asunción, Santa Maria and Buenos Aires cities. Ji Paraná, Cuiabá, Santa Cruz and Campo Grande AOD stations are located in red.

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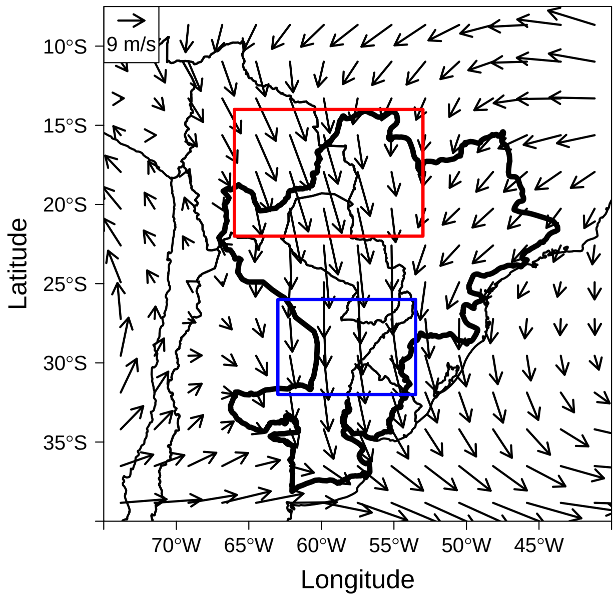

Fig. 3. Mean wind of north flow cases. Blue rectangle represents the study area, red rectangle is an auxiliary region for the filter and thick black contour delimits La Plata Basin.

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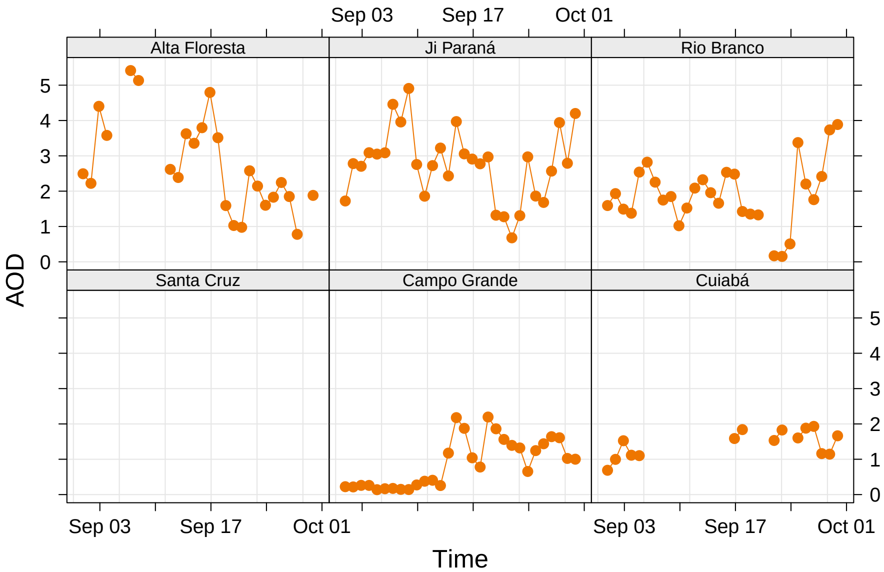

Fig. 4. AOD measurements from AERONET sunphometers during September 2007.

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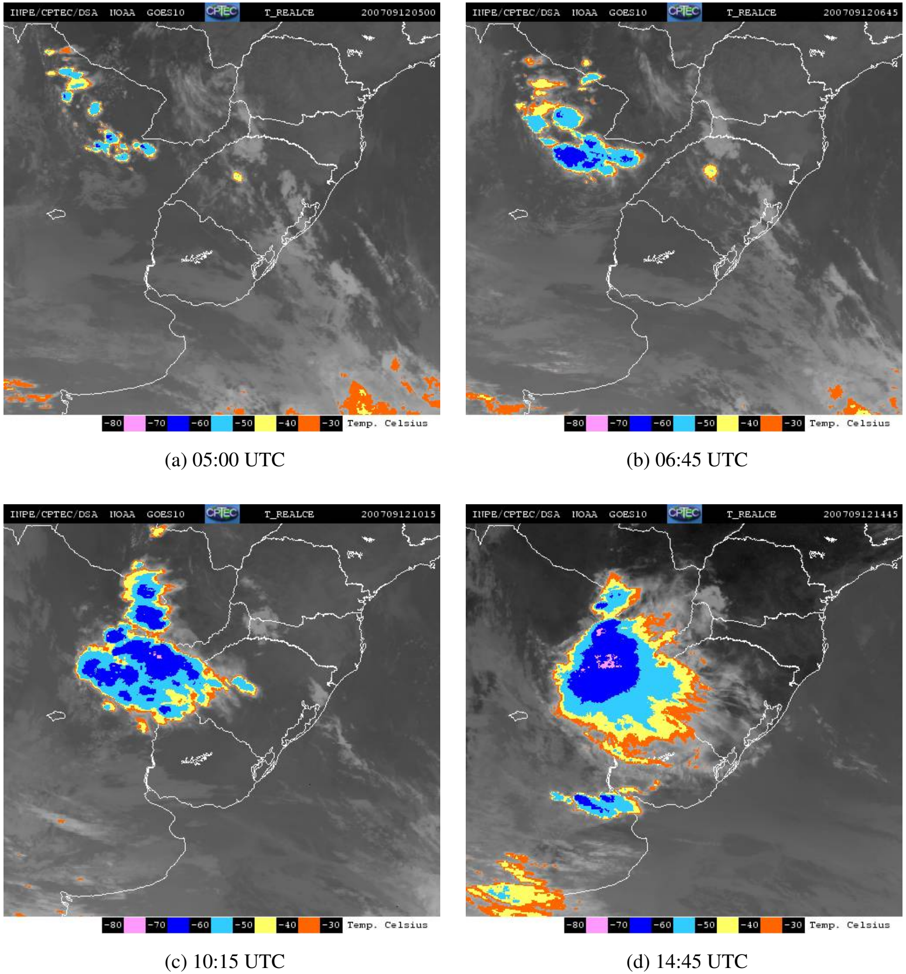

Fig. 5. Enhanced satellite images from GOES 11 infrared channel at 12 September 2007.

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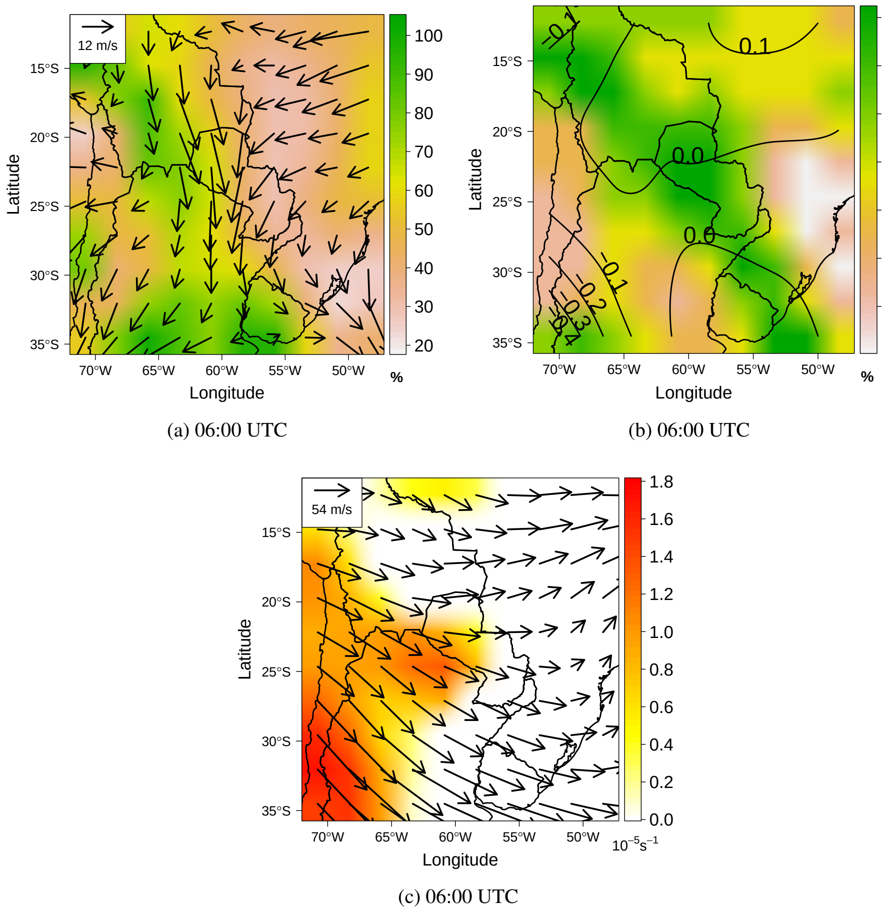

Fig. 6. Wind and relative humidity field at 850 hPa **(a)**, mean 700-500 hPa RH (shaded) and ω at 500 hPa (contour) **(b)**, and divergence field at 200 hPa **(c)**, all at 12 September 2007.

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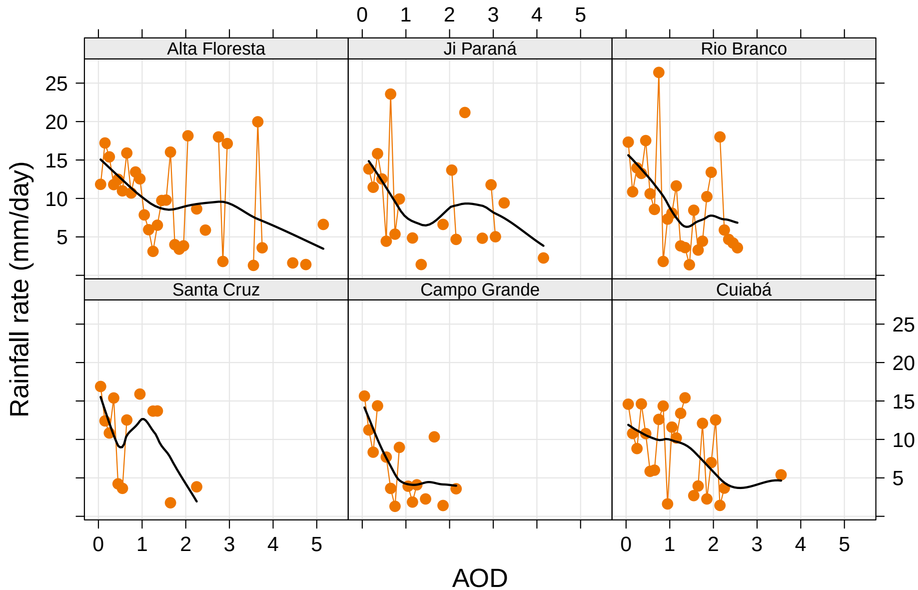

Fig. 7. Averaged rainfall rate binned by AOD for each station.

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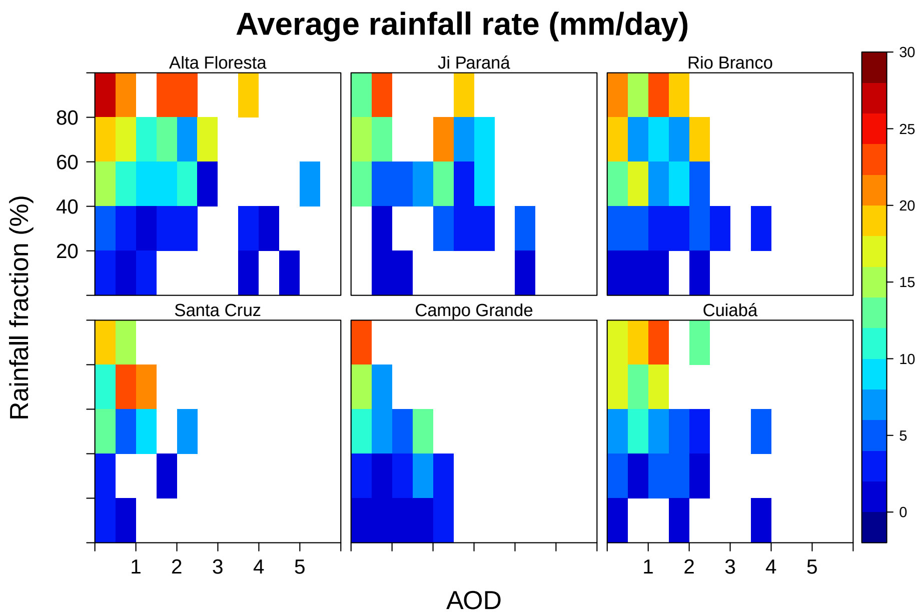

Fig. 8. Two-dimensional histogram of mean averaged rainfall rate for each station. Shaded boxes indicate mean averaged rainfall rate.

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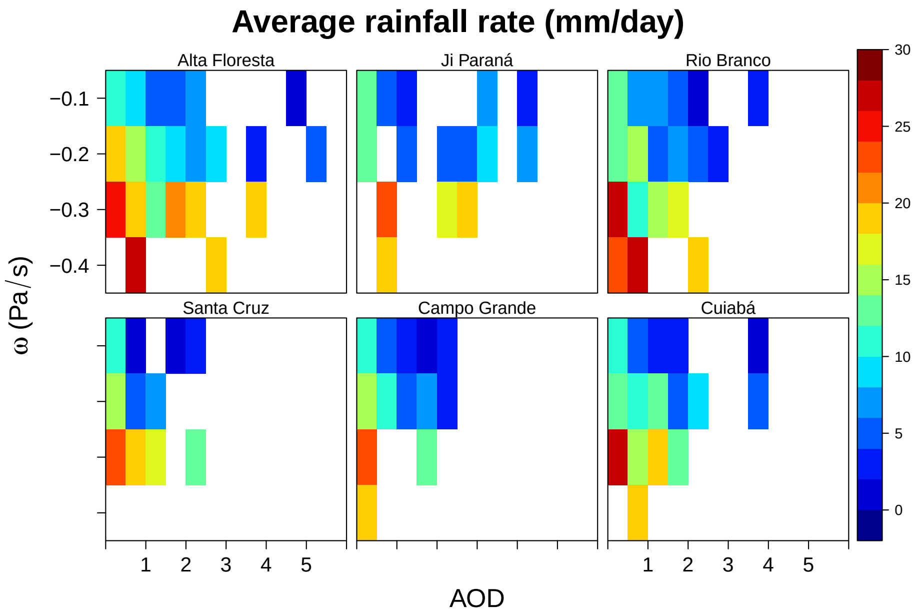

Fig. 9. Two-dimensional histogram of mean averaged rainfall rate for each AOD station. Shaded boxes indicate mean averaged rainfall rate.

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