Emissions from sugar cane fires in the Central & Western State of São Paulo and aerosol layers over metropolitan São Paulo observed by IPEN´s lidar: Is there a connection?

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ABSTRACT:

The central and western parts of the State of São Paulo are well-known for vast sugar cane plantations, which during the harvest time are traditionally burnt about 12 hours before manual cutting. This procedure causes the release of large quantities of aerosols and a variety of gases, which can be observed by IPMet's radars, located in Bauru and Presidente Prudente, on days with no or little rain. Depending on the distance of these plumes from the radar, they can be detected up to 5 km amsl or more, and are subsequently being transported by winds to other regions. During the dry winter season of 2008, such plumes, attributed to cane fires, were frequently observed by IPMet's radars and documented in terms of radar reflectivity, time and location during the period 10th – 21st July 2008. At the same time, IPEN's Elastic Backscatter Lidar in São Paulo observed layers of aerosols of variable strength and heights above the city. The most significant days, viz. 14 and 15 July 2008 had been selected for calculating backward, as well as forward trajectories, deploying the European Flextra 3.3 Trajectory Model, which was initiated with ECMWF historic data with a 0,25°×0,25° grid spacing. The results presented here show an excellent match between the radar-detected sources of the plumes on 11th July 2008 in the central parts of the State and the observations by IPEN's Lidar over Metropolitan São Paulo on 14th July 2008, both in terms of forward and backward trajectories, as well as their heights, with a transport duration of approximately 70 hours under the prevailing meteorological conditions.

Key words: Sugar Cane Fires, Radar Observations, Elastic Backscatter Lidar, Aerosol Trajectories, Flextra 3.3 Trajectory Model, State of São Paulo, Brazil..

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1. Introduction

The central and western parts of the State of São Paulo are well-known for vast sugar cane plantations, which during the harvest time (approximately April – November) are traditionally burnt about 12 hours before manual cutting. This procedure causes the release of large quantities of aerosols and a variety of gases, which can be observed by IPMet's (Instituto de Pesquisas Meteorológicas) radars, located in Bauru and Presidente Prudente (Fig. 1), on days with no or little rain. Depending on the temperature of these plumes, surface winds and their distance from the radar, they can be detected up to 5 km amsl (above mean sea level) or more by the radars, but the diluted plume certainly rises much higher than that, and is subsequently being transported by winds to other regions.

During the dry winter season of 2008, such plumes, attributed to cane fires, were frequently observed by IPMet's radars and documented in terms of radar reflectivity, time and location during the period 10th – 21st July 2008. During this period, IPEN's Elastic Backscatter Lidar in São Paulo observed layers of aerosols of variable strength and heights above the city. The most significant days, viz. 14th and 15th July 2008 had been selected for calculating backward, as well as forward trajectories. Initial attempts, using locally available trajectory models, like HYSPLIT and BRAMS, turned out to be unsuccessful, possibly due to insufficient resolution or a limited domain. Therefore, a joint project was established during a technical visit in Orleans, France, to run backward and forward trajectories in collaboration with the Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2E), CNRS (Centre National de la Recherche Scientifique), Université d'Orleans with the European Flextra 3.3 Trajectory model [1], using ECMWF historic data.

Fig. 1. PMet's Radar Network (PPR = Presidente Prudente; BRU = Bauru), showing 240 and 450 km range rings. The location of IPEN in São Palo is also shown.

2. Method and data

2.1 Radar

Figure 1 shows the range of the IPMet S-band Doppler radars, located in Bauru (Lat: 22°21'28" S, Lon: 49°01'36" W, 624 m amsl) and in Presidente Prudente, 240 km west of Bauru (Lat: 22°10'30" S, Lon: 51°22'22" W, 460 m amsl). Both have a 2° beam width and a range of 450 km for surveillance, but when operated in volume-scan mode every 7,5 minutes it is limited to 240 km, with a resolution of 250 m

radially and 1° in azimuth, recording reflectivities and radial velocities [2]. The reflectivity threshold for this study was set at 6 dBZ. Both radars have Sigmet processors and run under the IRIS Operating System. Radar images are presented as PPI (Plan Position Indicator) or CAPPI (Constant Altitude PPI, 240 km range) either individually per radar or merged.

2.2 IPEN's aerosol lidar

The IPEN Elastic Backscatter Lidar System is permanently installed in São Paulo and based on the Campus of the University of São Paulo (Lat: 23°33' S, Lon: 46°44' W, 840 m amsl; Figure 1). It comprises a commercial Nd:YAG laser operating at the second harmonic frequency at 532 nm wavelength, with a repetition rate of 20 Hz and energy pulse as high as 100 mJ. The optical receiver system consists of a Newtonian telescope with a 30 cm diameter, a 1-2 mrad of field of view and 1.3 m focal length. The backscatter laser radiation is detected by a Hamamatsu R7400 photomultiplier coupled to narrow band interferences filters with 1 nm FWHM. The photomultiplier output signal is digitalized and stored by a Lidar Transient Recorder LR 20-80/160 (LICEL-GmBh) which has an acquisition analog channel with 12 bits of resolution at 40 MHz. The data are averaged with a typical spatial resolution of 15 to 30 m. A more detailed description is provided in [3].

2.3 Flextra trajectory model

The Lagrangian model FLEXTRA is a kinematic trajectory model initially developed in at the Universität für Bodenkultur in Vienna (Version 2; [4]) and later refined at the University Munich (Version 3.3; [1]), to calculate different types of forward and backward trajectories, specifically for long time sequences for many receptor locations. It was deployed to calculate three-dimensional 96- and 120-hour backward and forward trajectories. The FLEXTRA model uses bicubic horizontal, quadratic vertical and linear time interpolation to determine the three wind components at a trajectory position and employs the numerical method of Petterssen [5] for the trajectory calculation. The model has been validated with constant level balloon flights [6],

manned gas balloon flights [7] and meteorological tracers [8].

The model was driven with wind fields extracted from ECMWF (European Centre for Medium-Range Weather Forecasts) for a domain from -180° to +180° longitude and -05° to -40° latitude and 91 levels, every 6 hours, ensuring sufficient boundary conditions for the trajectories to be generated.

The domain within which the trajectories were visualized and analyzed covered the region from -18,5° to -40° latitude and -30° to -70° longitude (Fig. 2). The backward trajectories were created using 8 points spaced around the Lidar position at 0,25°, starting at the time and heights where the aerosol layers were observed. Runs were performed with heights above mean sea level, as well as in hPa coordinates. The forward trajectories were initiated at the time and position of the most intense radar signal at 930 hPa (just above ground), with the other starting points stacked at 30 hPa height intervals up to 450 hPa, in order to account for the plume rise. There is no deposition during transport.

The visualization of the trajectories was done with the free R software environment for statistical computing and graphics [9].
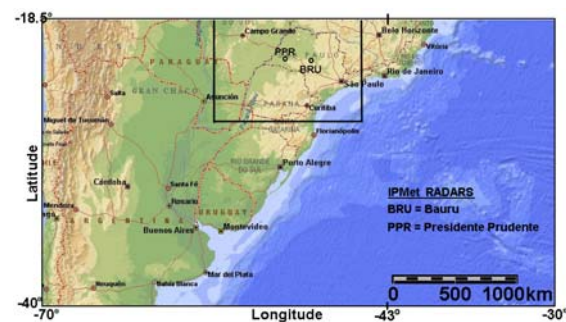

Fig. 2. Domain of the Flextra model in which the trajectories were visualized and analyzed. The inserted rectangular coincides with the radar map shown in Fig 1.

3. Observations

3.1 Synoptic situation

The period 11th-15th July 2008 was characterized by a dry air mass associated with the circulation of a dominant High pressure system, situated over the Southeast and Central-east regions of

Brazil, thus preventing the formation of clouds, as illustrated by the GOES-10 images in Fig. 3.

3.2 Lidar observations

IPEN's Lidar in São Paulo was operated intermittently between 10th and 21st July 2008, but the most significant observations were recorded on 14th and 15th July, which were thought to have been caused by sugar cane fire plumes from the interior of the State (Fig. 4).

The heavy urban pollution / aerosol load can be seen in the layers up to 1 – 2 km AGL (above ground level), but significant layers of aerosols are also visible between 4,0 – 5,5 km AGL on 14 July and between 2,5 – 3,0 km AGL on 15 July. Detailed scrutiny of the data reveals more, but less dense layers above and below as well.

3.3 Radar observations

The above observations prompted an analysis of the routinely acquired surveillance images (PPI at 0,3° elevation, 450 km range) of the PPR and BRU radars of IPMet during the preceding 5 – 10 days. Since no rain fell during this period, all medium to strong radar echoes could be attributed to emissions from sugar cane fires. These fires commonly have durations of a bit more than one hour, and therefore might only appear on 1 or 2 PPI, because in the absence of rain echoes the routine scanning cycle of the radars is one PPI every 30 or 60 min.

A typical example of a large cane fire ca 60 km south-east of the Bauru radar, indicating a reflectivity of 28 dBZ is depicted in Fig. 5. A set of forward trajectories was initiated from this point, reaching IPEN after 70 hours, i.e., at 20:00 UT (17:00 LT) on 14 July at a height of 4455 m, which matches well the Lidar observations (Fig. 4, top).
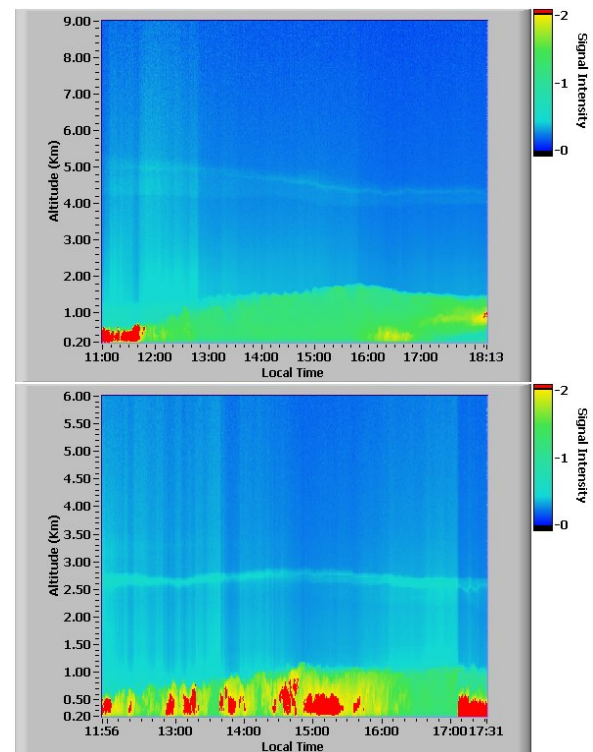

Fig. 4. Lidar Observations at IPEN in São Paulo, showing the range corrected signal in arbitrary units, on 14 (top) and 15th July 2008 (bottom).
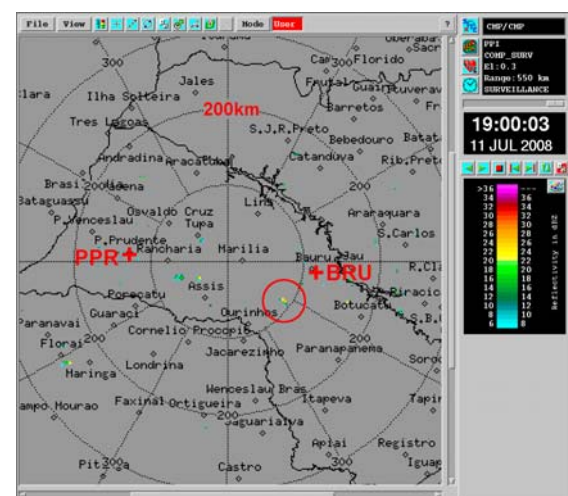

Fig. 5. Composite PPI of IPMet's Radars (PPR and BRU; elevation 0,3°) on 11th July 2008 at 19:00 LT. The red circle marks the position of one of the fires from which the forward trajectories were initiated.

Fig. 3. Daily GOES-10 Satellite Images at about 12 LT (Local Time) from 11th–14th July 2008 (courtesy INPE/CPTEC).

Figure 6 shows a typical plume rising from a sugar cane fire. The detailed 3-dimensional structure of emissions from such fires can be observed, if IPMet's radars operate in Volume Scan Mode. Such an example of a strong sugar cane fire on 17th July 2008, 70 – 80 km east-north-east of Bauru, with the plume extending up to 4,5 km amsl, is shown in Fig. 7.
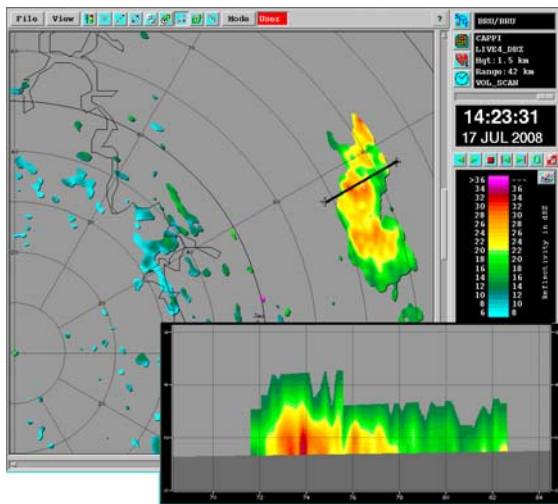

Fig. 6. Typical plume from a sugar cane fire.

Fig. 7. CAPPI at 1,5 km amsl of Bauru radar on 17th July 2008, 14:23 LT, range rings every 10 km, reflectivity levels 6 to >36 dBZ; vertical cross-section along the black base-line with the vertical scale from 0 – 6 km amsl.

4. Analysis of trajectories

Back trajectories were initiated at different heights and times above IPEN in São Paulo, based on the Lidar observations. The example in Fig. 8 shows 9 back trajectories, initiated on 14 July 2008, 15:00 UT (12:00 LT), at 6 km above mean sea level (amsl) from a grid at longitude −46,73° ± 0,25° and latitude −23,55° ± 0,25°. The

starting points of all back tracks are centered around IPEN (Nr.5), with Nr.1 being on the NW corner, counting clockwise, as shown in the insert. The run time was 96 hours (four days) with trajectory points calculated hourly. As can be seen, these backward trajectories followed very different paths, although they all originated from an approximately 50×50 km square and some even extended beyond -180° westwards, reaching far beyond the west coast of the South American continent. Therefore, it was decided to initiate these trajectory ensembles from 2,5 km below and above the observed aerosol layers at 500 m height intervals.

Forward trajectories were initiated from radar echo positions, indicating fires generating an aerosol plume, at heights ranging from 930 hPa (close to ground level) up to 450 hPa (ca 6,7 km amsl) at 30 hPa intervals.
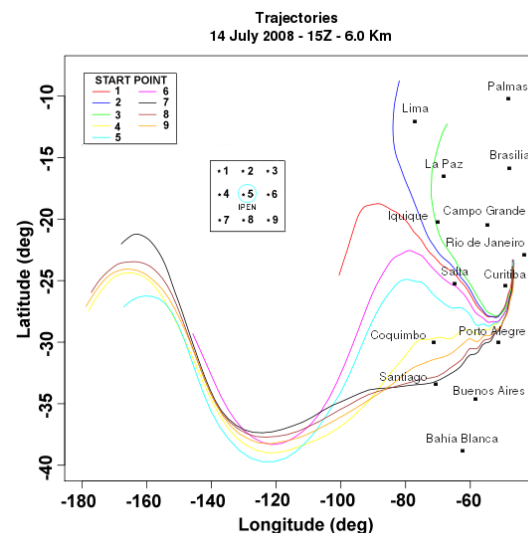

Fig. 8. Backward trajectories initiated at IPEN on 14th July 2008, 15:00UT at 6,0 km amsl. Run time 96 hours.

4.1 Backward Trajectories: 14 July 2008

Ensembles of backward trajectories were initiated hourly from IPEN on 14th July 2008 between 14:00 and 21:00 UT (11:00 - 18:00 LT). The most significant tracks are shown in Figs. 9a-d. These tracks confirm, that aerosol-laden air masses from the central and western interior of the State of São Paulo do reach the metropolitan Region (RMSP) under the prevailing synoptic situation during the period investigated, thus adding to the already critical urban pollution plume [10].
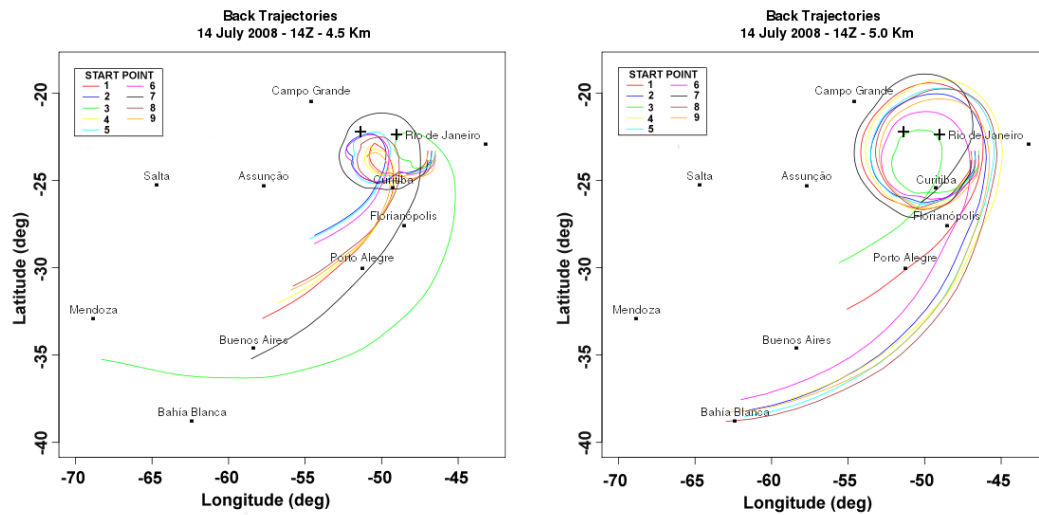
Fig. 9a. Backward trajectories initiated at IPEN on 14th July 2008, 14:00UT at 4,5 and 5,0 km amsl. The + indicates the position of the PPR and BRU radars.
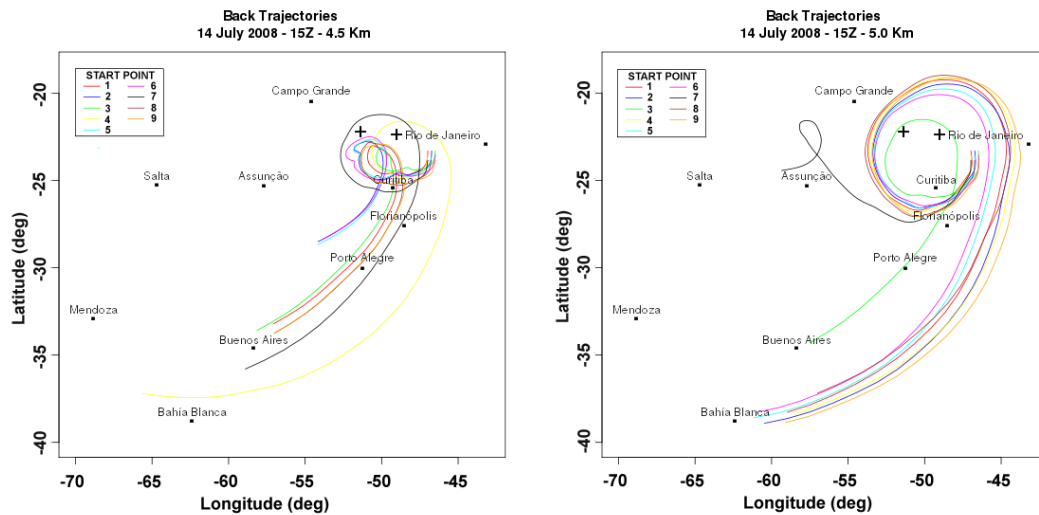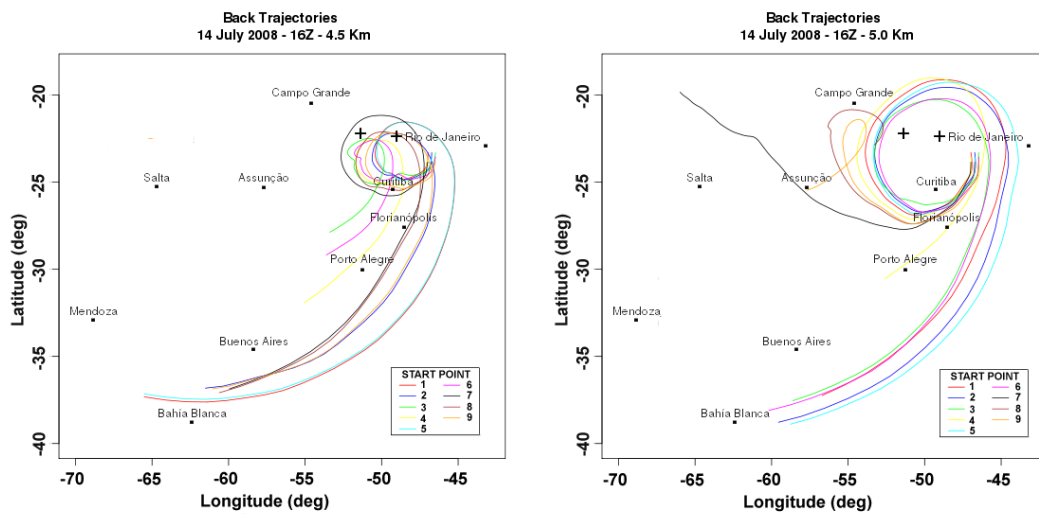

Fig. 9b. Same as Fig. 9a, but for 15:00UT.

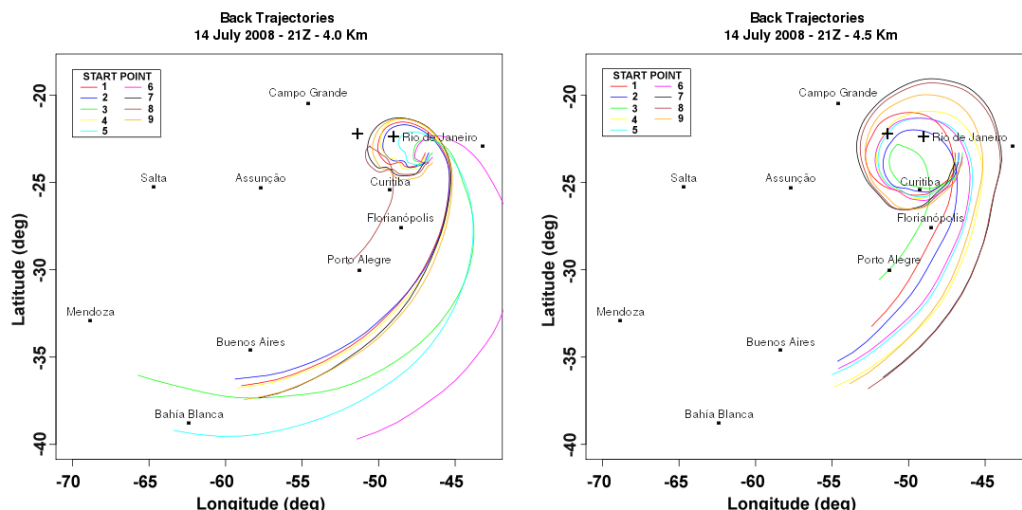Fig. 9c. Same as Fig. 9a, but for 16:00UT.

Fig. 9d. Same as Fig. 9a, but for 21:00UT at 4,0 and 4,5 km amsl.

4.2 Forward Trajectories: 11th July 2008

Figure 10 shows forward trajectories initiated on 11th July 2008 from locations where the radars detected significant sugar cane fires, at the following starting heights: 930, 870, 810, 750, 570, 550, 540, 530, 520, 510 hPa (run time 96 h).

Flextra 3.3 calculates the trajectories in three dimensions, viz., x, y (output in longitude and latitude) and z, which can be in m or hPa. Therefore, time-versus-height graphs are very useful for completing the 3-dimensional time history of the trajectories. For instance, if a trajectory at any time during its transport comes close to ground level, it could collect more aerosols or other pollutants (e.g., gases, which might react during the transport and convert to aerosols). That would have to be considered when interpreting the Lidar observations. Also, if a trajectory fluctuates over a large range of heights, it would be indicative of a significant dilution of the aerosol and gaseous content of the air parcel being transported along that trajectory.

The trajectories shown in Fig. 10d for 22:00 UT are represented as a height x time graph in Fig. 11. The cross (+) marks the exact height and time when one of the trajectories, initiated at about 5,5 km above the source, traversed IPEN. It arrived there after 70 hours, i.e., at 17:00 LT at a height of 4,5 km amsl. This coincides exactly with the Lidar observations (Fig. 4).

Considering the very good results obtained in this study, it must, however be emphasized, that they are only based on one case under specific synoptic conditions. The analysis is ongoing to include more lidar observations and relate them to radar-detected sugar cane fires in the central and western interior of the State. Furthermore, it is proposed to improve the trajectory visualization by adding regular time marks and a map overlay.
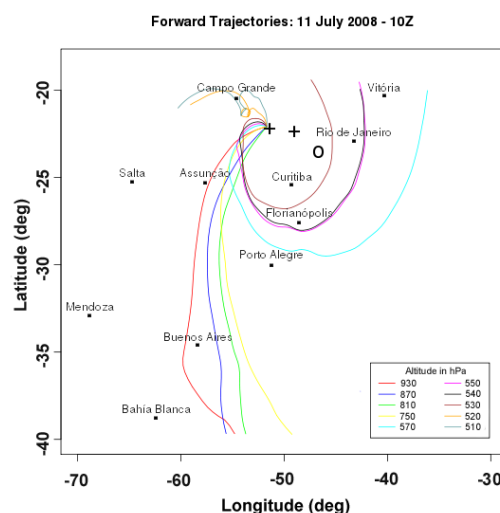

Fig. 10a. Forward trajectories initiated where fires were indicated by IPMet's radars on 11th July 2008, 10:00UT (07:00 LT). The + indicates the position of the PPR and BRU radars; o indicates IPEN, starting point of the backward trajectories.
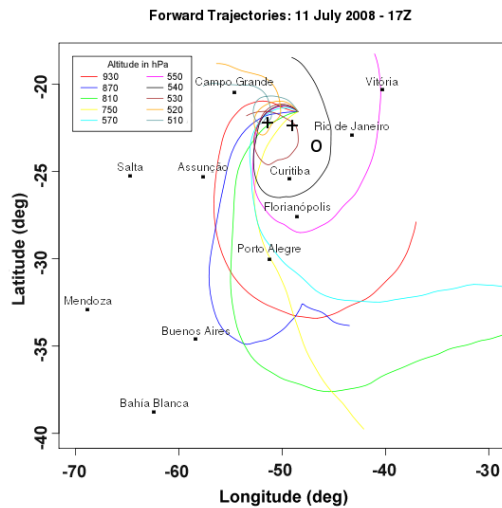
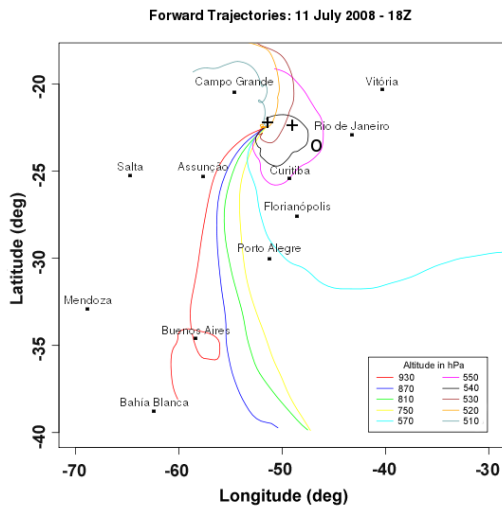Fig. 10b. Same as Fig. 10a, but for 17:00UT (14:00 LT).

Fig. 10c. Same as Fig. 10a, but for 18:00UT (15:00 LT).
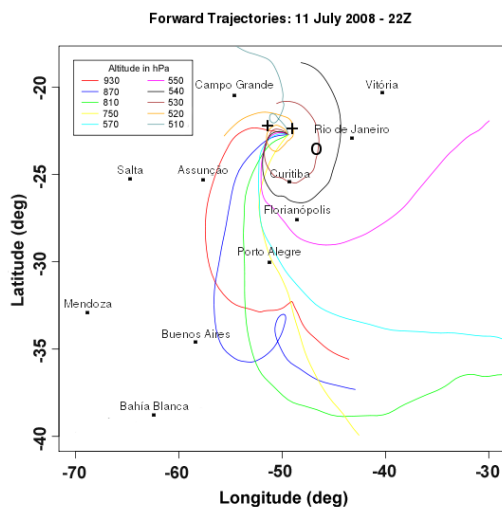

Fig. 10d. Same as Fig. 10a, but for 22:00UT (19:00 LT).
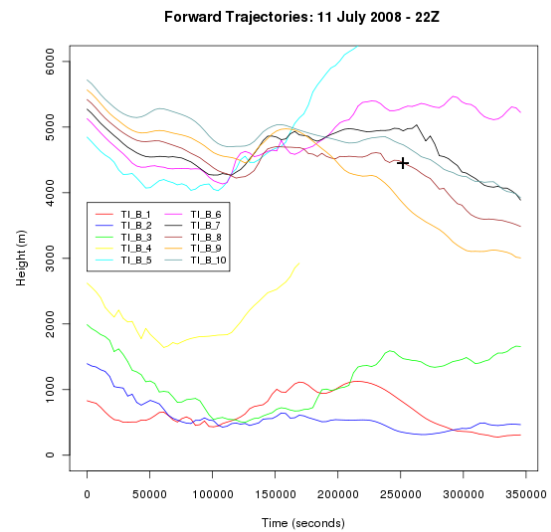

Fig. 11. Forward trajectories initiated on 11 July 2008, 22:00UT (19:00 LT), plotted against height and time. The + indicates the position of IPEN, marking height and time of arrival.

5. Conclusions

During July 2008, layers of aerosols had been observed by IPEN's Elastic Backscatter Lidar in São Paulo, while emissions from sugar can fires in the central and western State of São Paulo were identified by IPMet's Doppler Radars during this rain-free period.

YES, there is a connection between aerosol layers observed by IPEN's Lidar in São Paulo City and emissions from sugar cane fires in the central and western interior of the State, as demonstrated by forward and backward trajectories.

However, initial tests using HYSPLIT and BRAMS to generate backward trajectories could not provide reasonable answers, most likely due to their windfields and grid resolution being too coarse and the model domain too small.

Therefore, windfields were downloaded from the ECMWF data base with a grid spacing of 0,25º x 0,25º (6-hourly) for a domain ranging from -180° to +180° longitude and -05° to -40° latitude and 91 levels.

Matching backward and forward trajectories could be identified for emissions from sugar cane fires in the interior of the State on 11th July 2008 and observations of aerosol layers over

metropolitan São Paulo during the afternoon of 14th July 2008.

It is therefore important to have a high-resolution three-dimensional windfield available as input for generating trajectories in hourly time steps.

In this particular case study, it took approximately 3 days for the aerosols to reach metropolitan São Paulo;

The analysis is ongoing with observations relating to 15th July 2008, which occurred during the same synoptic conditions, but further cases will also be investigated.