HOLOS ENVIRONMENT

ICESAT-2 LIDAR RETRIEVALS FOR A SMOKE AND CLOUDS CASE: ESTIMATES IN THE SOUTH AMERICA REGION

RECUPERAÇÕES DO ICESAT-2 LIDAR PARA UM CASO DE FUMAÇA E NUVENS: ESTIMATIVAS NA REGIÃO DA AMÉRICA DO SUL

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Abstract: The present study aims to estimate the height of smoke aerosols and clouds from the Advanced Topographic Laser Altimeter System (ATLAS) instrument sensor onboard the Ice, Cloud and land Elevation Satellite-2 (ICESat-2). The study was conducted during the dry season on September 14th of 2020, when there was a large number spot of biomass burning fires and smoke aerosol layers over the Amazon and the South American region. Most often, the smoke plumes move with southward winds, along the east of the Andes. During this period occasionally polar cold fronts move from the south, meeting the smoke aerosol layers. Initially, daily images from the polar orbit satellites such as Terra, Aqua, NOAA and Suomi were used to identify the spatial location of smoke plumes and clouds over the region. Then, ICESat-2 tracks were analyzed to evaluate their presence in the study area. The results show that ICESat-2 data retrieval is able to estimate the height of the aerosol layer and the top of the cloud. Some tracks show clearly higher clouds, with tops reaching about 12-13 km, when there is the presence of a cold front or deep convective cumulonimbus. Over clear sky regions where smoke is observed, estimated heights from the lidar are on the order of 3-4 km. Local profiles of temperature obtained from radiosondes show inversion layers at similar heights as detected by the lidar sensor. These inversion layers seem to be associated with the warming effect of the absorbing biomass burning aerosols.

Keywords: Biomass aerosols. Black carbon. Amazon rainforest. South America.

Resumo: O presente estudo visa estimar a altura das camadas de aerossóis de fumaça e nuvens com uso do sensor ATLAS "Advanced Topographic Laser Altimeter System" a bordo do satélite ICESat-2 "Ice, Cloud and land Elevation Satellite-2". Neste estudo de caso, realizado durante a estação seca de 14 de setembro de 2020, foi observado um grande número de focos de incêndio e uma ampla camada de aerossóis de fumaça sobre a Amazônia e regiões adjacentes. Na maioria das vezes, as plumas de fumaça movem-se com ventos na direção sul, ao longo do leste dos Andes. Durante este período, ocasionalmente, as frentes polares deslocam-se de sul ao encontro destas plumas de fumaça. Inicialmente, utilizamos imagens diárias dos satélites da órbita polar como Terra, Aqua, NOAA e Suomi para identificar a localização espacial das plumas de fumaça e nuvens sobre a região. Em seguida, as órbitas do ICESat-2 foram identificadas para verificar sua presença na região de estudo. Os resultados mostram que os dados medidos pelo ICESat-2 conseguem estimar a altura da camada de aerossóis e do topo das nuvens. Em alguns locais os dados mostram nuvens altas, com topos que atingem cerca de 12-13 km, quando há a presença de uma frente fria ou de um cumulonimbus. Em regiões de céu claro onde se observam plumas de aerosóis, as alturas estimadas a partir do lidar são da ordem dos 3-

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4 km. Os perfis locais de temperatura obtidos a partir de radiossondas mostram camadas de inversão em altitudes similares às detectadas pelo lidar. Estas camadas de inversão parecem estar associadas ao efeito de aquecimento dos aerossóis como o carbono negro.

Palavras-chave: Aerosóis de biomassa. Carbono negro. Amazônia. América do Sul.

1 INTRODUCTION

The wet season in tropical South America occurs during the austral summer (Marengo *et al.*, 2001), when the Intertropical Convergence Zone (ITCZ) is located in its southernmost latitude, transporting high amounts of moisture towards tropical South America. Conversely, the dry season usually starts during the austral winter and extends towards the early spring. September corresponds to one of the driest periods in the region as the ITCZ moves to the northernmost latitude in the tropical northern hemisphere.

The South America fire season occurs mainly during September when there is a large number of biomass burning fires and smoke aerosols over the Amazon and the South American region (PINTO *et al.,* 2021). Most often, the smoke plumes move with southward winds, along the east of the Andes caused by South America low-level jet (SALLJ) according to observations by Marengo *et al.* (2004). During this period occasionally polar cold fronts move from the south meeting the smoke aerosol plumes (Fig. 01).

The incomplete biomass burning of vegetation emits several components, including gases and particles (ANDREAE, 2019). The major emitted gases are carbon monoxide (CO), nitrogen oxide (NOx), carbon dioxide (CO2), methane (CH4), and volatile organic compounds (VOCs). Beyond gases, it also emits primary organic aerosol and black carbon.

Black Carbon emissions from these fires have the optical property to absorb solar radiation. Thus, their presence can affect the atmospheric thermodynamics, such as the local radiation balance and air temperature. Atmospheric measurements of biomass burning aerosols show the absorbing properties of organic aerosols and black carbon (CORR *et al.,* 2012). Numerical simulations with and without the observed biomass burning aerosols show that the warming effect can create a stable layer decreasing the cloud formation (THORNHILL *et al.,* 2018). Recent results show that the absorbing properties of the smoke aerosols can stabilize the atmosphere causing a decrease in the temperature of clouds glaciation (CORREIA *et al.*, 2021).

Remote sensing became an essential tool for land-surface, clouds and aerosols monitoring for larger areas. It includes the polar orbit platforms (e.g. MODIS, CALIPSO) and the geostationary satellites such as the GOES and Meteosat (JURY; PABÓN, 2021; MARENCO *et al.*, 2014). Furthermore, airborne lidar flights during biomass burning of the Amazon in September of 2002 show that biomass aerosols were located on the levels near the surface and over levels reaching 4-6 km height (MARENCO *et al.*, 2016).

The new Ice, Cloud and land Elevation Satellite-2 (ICESat-2) satellite, launched in 2018, has a lidar onboard that sends individual fótons to the Earth and estimates surface heights from the travel time of these fótons back to its receptor (NEWMANN *et al.*, 2019). In their retrieval data applications, it includes height estimates of land, forest vegetation, ice, ocean waves, clouds and aerosol layers.

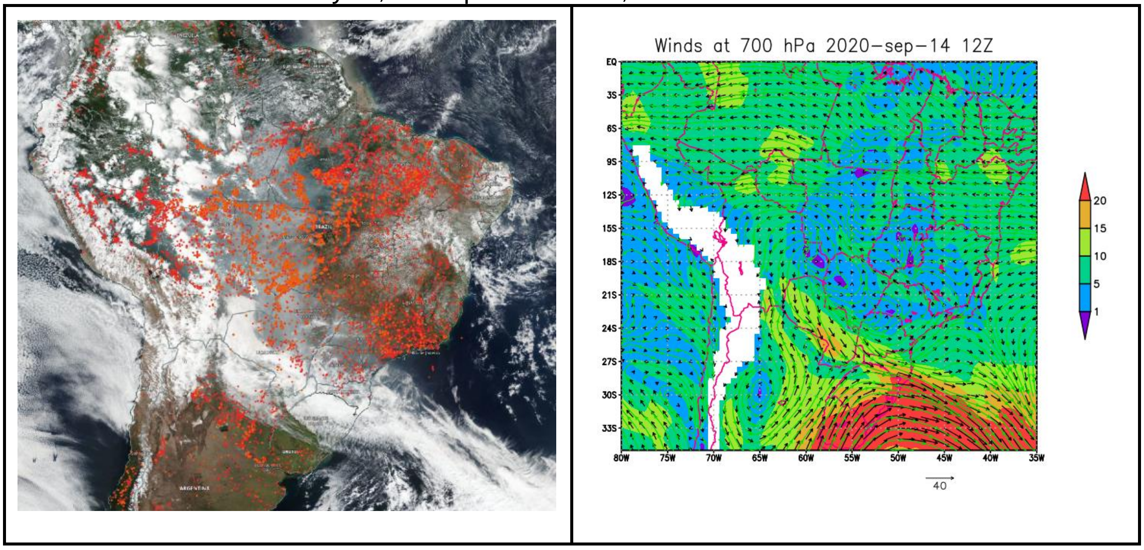
The present study aims to estimate the smoke aerosols and clouds from the Advanced Topographic Laser Altimeter System (ATLAS) instrument sensor onboard the ICESat-2. The study was conducted for September of 2020 when there was a large number of biomass burning fires and smoke aerosols over the Amazon and the South American region.

2 MATERIAL AND METHODS

2.1 The region of study

The region of study includes the centre of the South America region, where large areas of biomass smoke can be observed (Fig. 01). The snapshot satellite image shows a high number of fire spots over the region associated with broad areas covered with smoke aerosols (Fig. 1a). Near the south of the domain, deep clouds are formed due to a cold front moving from the south. In general, winds near the east coast of the Andes are southward and carry the smoke towards the south, supported by the presence of a cyclonic circulation located on the southeast coast of South America (Fig. 1b).

Figure 01 - (a) Suomi satellite image and fire spots, (b) wind flow vectors and speed at 700 hPa from MERRA reanalysis, for September 14th, 2020



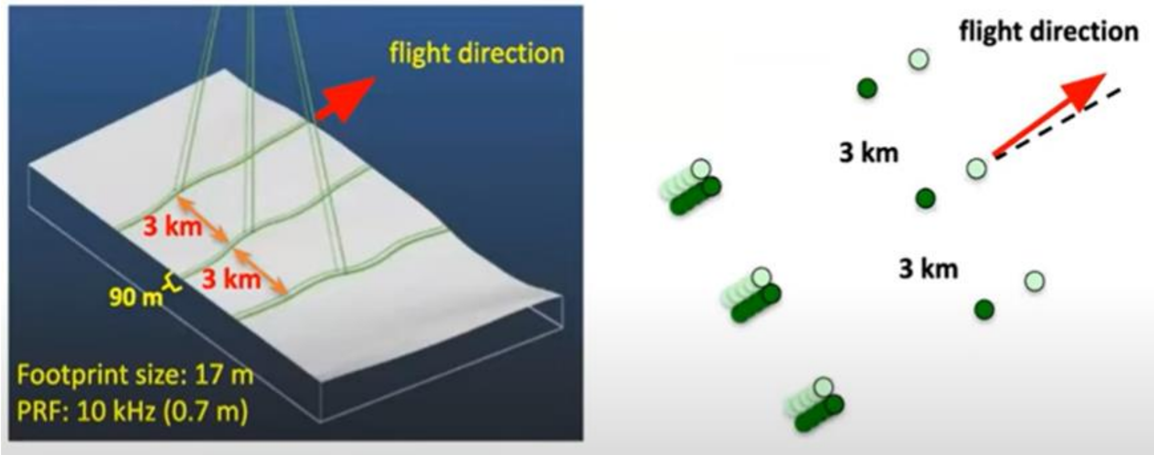
2.2 The polar orbit satellite images

Initially, daily images from the polar orbit satellites such as Terra, Aqua, NOAA and Suomi were used to identify the spatial location of smoke plumes and clouds over the region. These images are freely available from the NASA portal at https://worldview.earthdata.nasa.gov/. The period analyzed covered daily images for the dry season of September 2020, when large areas of smoke usually were detected. The ICESat-2 tracks were analyzed to evaluate the presence of these features, and a particular day was selected based on three criteria: large areas of smoke aerosols presence, ICESat-2 tracks presence over the South America smoke region and availability of radiosonde profiles near the observed satellite tracks.

2.3 The Icesat-2 lidar data

The ICESat-2 was launched on 15 September 2018. The satellite flies in a polar orbit at 500 km of height. Its laser altimeter uses a 532 nm lidar to measure the time of the fótons flight and thus the surface height from its six laser beams (NEUMANN *et al.*, 2019). The beams have a 30 m distance from the pairs (Fig 2). The laser sends about 20 trillion photons per pulse and only about a dozen return to its telescope.

Figure 02 - ICESat-2 satellite orbit and lidar design.



The ICESat-2 data were obtained from the NASA Earthdata portal where we can select the region and time of interest (see https://search.earthdata.nasa.gov/search). Two tracks were selected for South America on 14th September 2020 where the ascendant track (red line) crossed the study area between 8:20 and 9:55 UTC and the descendent track (blue line) crossed between 20:55 and 22:30 UTC (Figure 03). This particular day was selected for analysis because there was a high concentration of smoke aerosols over large areas and there were radiosonde observations available nearby the selected satellite tracks.

2.4 Atmospheric winds and radiosondes temperature profiles

Atmospheric wind components were obtained from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis. This data is available at NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC) through https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/ . Wind vectors were analyzed at 700 hPa level (about 3.2 km height) where the SALLJ flows east of the Andes (Fig. 1b).

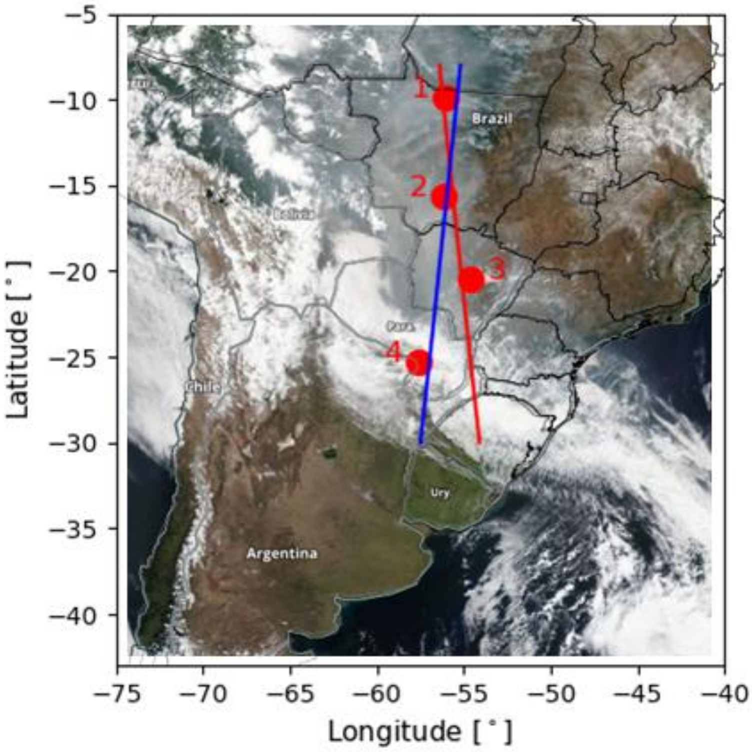
Four temperature profiles over selected smoke locations were obtained in order to evaluate the thermodynamics structure as shown in Table 01. The radiosondes are located at the airports of Alta Floresta, Cuiabá, Campo Grande and Asuncion cities and they were measured at 12h UTC. These profiles are freely obtained from the University of Wyoming data portal (http://weather.uwyo.edu/upperair/sounding.html).

Skew-T thermodynamics diagrams were produced to investigate the atmospheric thermal structure.

Table 01 - Radiosondes stations locations used when the ICESat-2 crossed the central-west of South America on 14th September 2020.

N	Station	Latitude	Longitude	Number/Symbol
1	Alta Floresta-MT	-9.86	-56,10	82965 SBAT
2	Cuiabá-MT	-15.65	-56.12	83362 SBCY
3	Campo Grande-MS	-20,46	-54,66	83612 SBCG
4	Asuncion/Paraguay	-25,26	-57,63	86218 SGAS

Figure 3 – Suomi satellite image smoke and clouds on 14th September 2020 with measurements of the lidar from ICESat-2 in the ascendant path (red line) and the descendent path (blue line) and temperature profiles from four radiosondes in this region



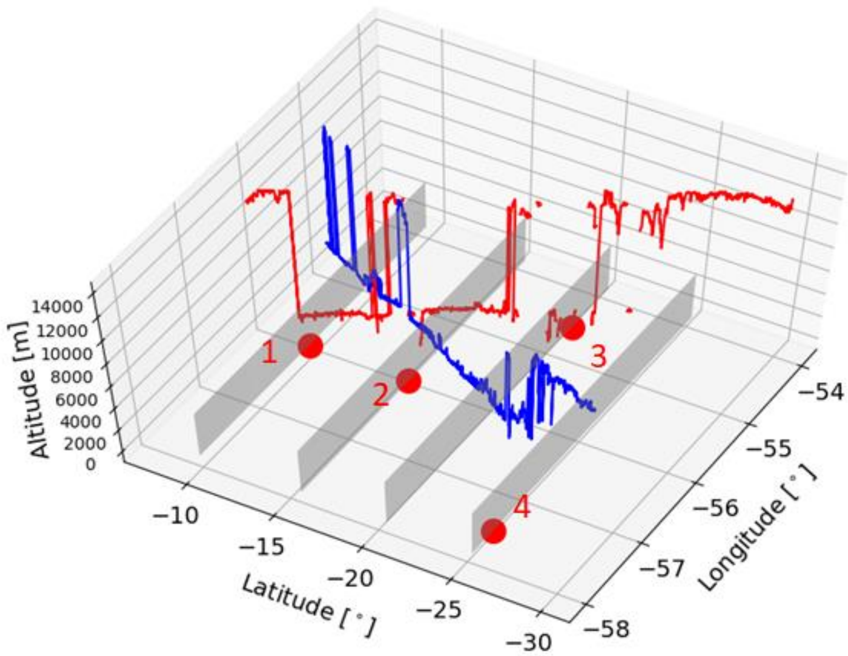
The heights of the smoke plume were estimated by the ICESat-2 at these positions using an average of all data available into an interval of ±0.02° of each latitude that the radiosondes are located, which represents about 15 data points.

The script in python used on the estimates and figures production are available at https://zenodo.org/record/5723963#.YZ4eDdDMKUk .

3 RESULTS AND DISCUSSION

The results show the height of the cloud top and smoke plumes measured by the Lidar onboard from ICESat-2. It also compares the inversion layer height of the atmosphere from four selected radiosondes located closer to the paths of ICESat-2 that crossed the central region of South America on 14th September 2020 (see Figures 3, 4).

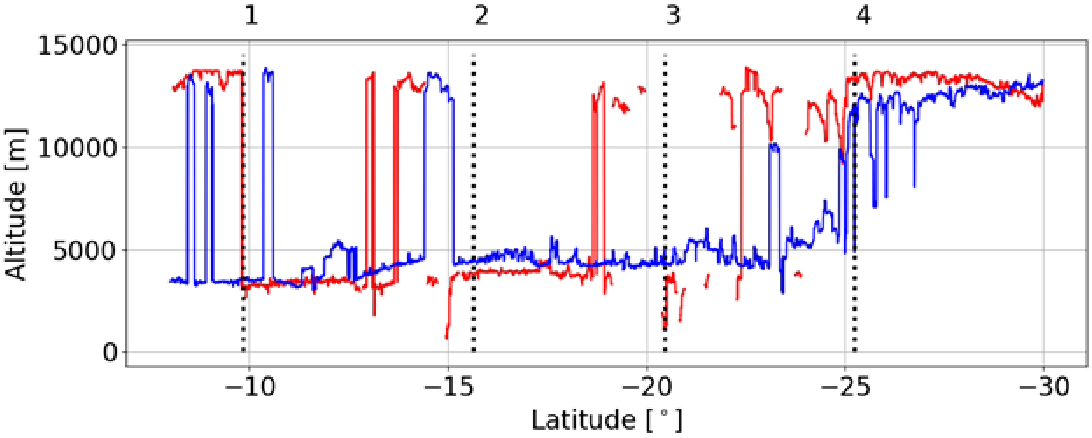
Figure 4 - Lidar measurements from ICESat-2 in the ascendant path (red line) and the descendent path (blue line) and the location of the four radiosondes (red dots).



The smoke plume occurs in a region of central South America that covers almost the whole area of the states of Mato Grosso and Mato Grosso do Sul states, where Alta Floresta (1), Cuiabá (2) and Campo Grande (3) are located (Figure 3, 4).
The average heights of the smoke plumes estimated from the ICESat-2 ascending/descending track orbits were 3,185 m / 3,553 m, 3,676 m / 4,477 m and 2,208 m / 4,684 m respectively as shown in Figure 5 and Table 2. The results show

that the aerosol plume height increases during the day as the satellite crossed the region at the local morning and early evening time, respectively. The estimate at Asuncion (4) displays a different height where a deep vertical cumulonimbus prevails with an average height of 13,280 m / 10,463 m.

Figure 5 - Meridional view of Lidar measurements from ICESat-2 in the ascendant path (red line) and the descendant path (blue line) with the latitude of the four radiosondes (back dash lines)



In Figure 6, the thermodynamic temperature profiles show an inversion layer from the radiosondes of Alta Floresta, Cuiabá and Campo Grande where the smoke plumes are presented as indicated in the satellite image from Figure 3. Conversely, the radiosonde in Asuncion represents an unstable condition with deep convective clouds developed at the site.

Figure 6 - Air Temperature (red line) and Dew Point temperature (blue line) from radiosonde of Alta Floresta (a), Cuiabá (b), Campo Grande (c) and Asuncion (d)

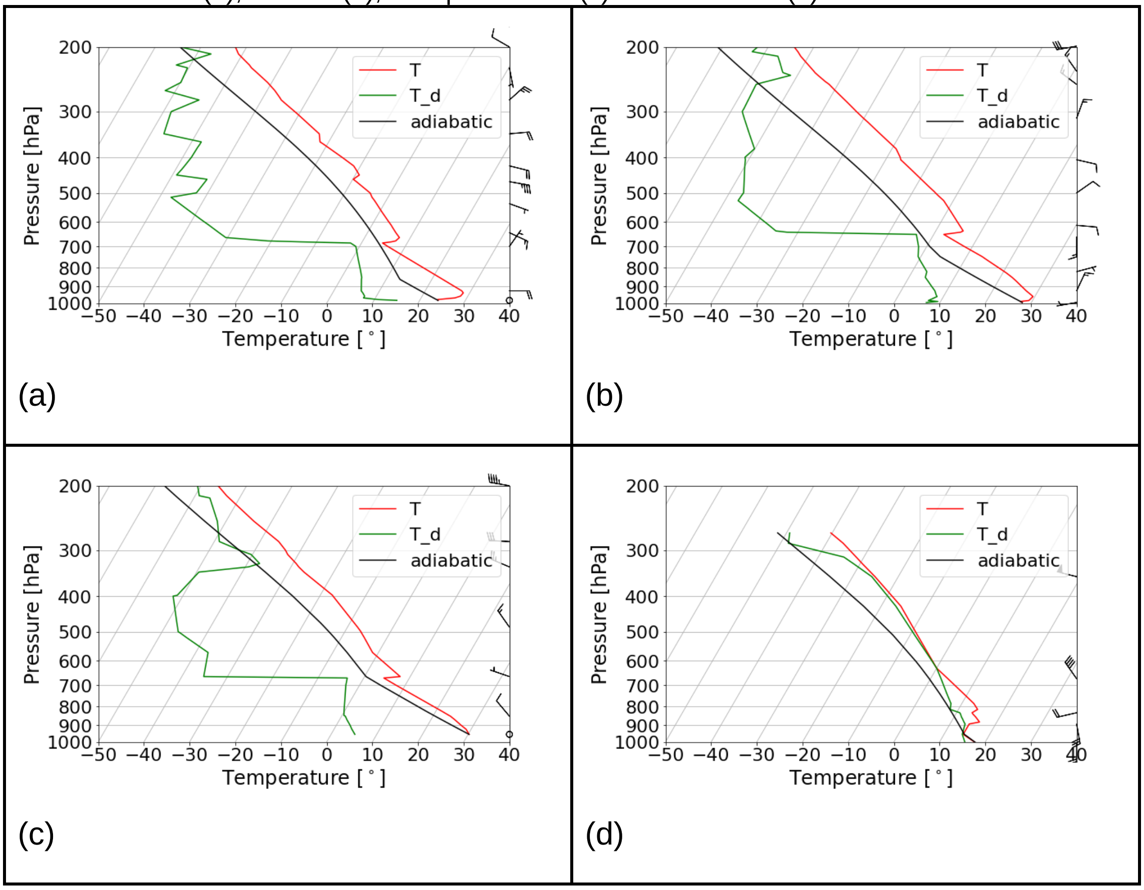


Table 02 - Average and standard deviation heights of the smoke plume from ICESat inversion layer and measured from the local radiosonde.

Station	top height - ascending [m]	top height - descending [m]	Inversion height radiosonde [m]
Alta Floresta	*3,185±23*	*3,553±14*	*3653*
Cuiabá	*3,676±76*	*4,477±71*	*4023*
Campo Grande	*2,208±1202*	*4,684±315*	*3664*
Asuncion	*13,280±55*	*10,463±2,438*	*

** due to deep clouds the radiosonde balloon reached only 10,4 km height.*

4 CONCLUSIONS

The ICESat-2 LIDAR is able to estimate the height of the aerosols and clouds top layers. Some track orbits measurements show clearly higher clouds, with tops reaching about 12-13 km when there is the presence of a cold front or deep convective cumulonimbus.

In clear sky regions where smoke is observed, estimated heights from the LIDAR were about 2.2-4.7 km. Local profiles of temperature obtained from radiosondes show inversion layers at a similar height detected by the LIDAR satellite sensor. These inversion layers seem to be associated with the warming effect of the absorbing biomass black carbon burning aerosols. The results agree with recent studies that show the impacts of these aerosols on the radiation balance, cloud properties and precipitation (ANDREAE *et al.*, 2004; ANDREAE; ROSENFELD, 2008; ROSENFELD *et al.*, 2008, 2014; WARD *et al.*, 2012; TOSCA *et al.*, 2013; JIANG *et al.*, 2016; BRAGA *et al.*, 2017; CECCHINI *et al.*, 2017; HAMILTON *et al.*, 2018; THORNHILL *et al.*, 2018).

These results show that the LIDAR onboard ICESat-2 is an important tool for monitoring this important region, as smoke seems to have an influence on the atmospheric thermodynamics, and clouds and rainfall formation.

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