A preliminary classification of cirrus cloud over São Paulo city by systematic lidar observations and comparison with CALIPSO and AERONET data

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ABSTRACT

Cirrus clouds in the upper troposphere and the lower stratosphere have received much attention recently due to their important role and impact on the atmospheric radiative balance. To understand and quantify its impact on Earth's atmosphere radiative transfer it is necessary to have information about its optical properties. Such a knowledge is necessary both for comparison with others datasets of cirrus measurements as well as for its influence on radiative transfer models. Cirrus clouds measurements have been performed since 2005 in the Metropolitan São Paulo, Brazil (23^{o}33'S, 46^{o}44'W). From MSP-lidar backscatter profiles at 532 nm, and eventually 355 nm, the cloud optical depth (COD) as well as the high of base and top of the clouds are retrieved. A preliminary climatology of cirrus clouds over São Paulo using this method has been set. The measurements from Aerosol Robotic Network (AERONET), the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and GOES-10 observations are compared with a ground based lidar dataset for a wide range of cloud types.

Keywords: LIDAR, Satellite, CALIPSO, Sub-Visual Cirrus

1. INTRODUCTION

Cirrus clouds, which regularly cover about 20% of the globe, have been identified as one of the major unsolved components in weather and climate research.[1] It is now understood that the cirrus clouds inhabiting the upper troposphere play a significant role in regulating the radiation balance of the earth-atmosphere system and so must be recognized as a crucial component in solving the human-induced climate change puzzle.[2] They influence weather and climate through their impact on the radiative energy budget of the atmosphere and unlike most boundary layer stratus and stratocumulus clouds that have a net cooling effect on the climate, high-level thin cirrus clouds have a warming effect on our climate.[2,3] The recent advances in cirrus cloud research capabilities have included aircraft probes, ground-based (and airborne) active remote sensing using lidar and radar, and passive radiometric probing, either from Earth-orbiting satellites or from the ground as part of multiple active/passive remote sensor techniques. Although these technologies are still evolving, it must be recognized that each method has its advantages and disadvantages.[3] The satellite cloud climatologies are constrained to reporting only one level for the clouds and do not define the vertical depth of the clouds, the vertical profile of visible extinction, or infrared absorption.[4] Other more recent sensors as MODIS(Moderate Resolution Imaging Spectrometer) are able to determine optical depths for aerosols and clouds, but especially if treating of cirrus, they are still not accurate. Among the drawbacks in satellite cirrus cloud retrieval are properly accounting for the effects of cloud fraction and spatial inhomogeneities; characterizing the background radiances; understanding nonspherical ice-particle scattering behavior; problems inherent in inferring cloud optical depth; and maintaining accurate instrument calibrations[5] and due to aerosol and chemical scavenging processes, the aerosols remaining

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after evaporation of cirrus clouds may be modified compared to the particles that were present before cloud processing. This processing of aerosols may affect their ice nucleations properties at later times and issuing complex approached to this type of study.[3] However, significant uncertainties exist in the detection of thin cirrus and the determination of their optical depth and composition,[6] most fundamental are the questions of how many cirrus clouds go undetected because they are too thin, and how many cold and high clouds are characterized as cirrus even though the clouds are the tops of deep cloud systems such as altostratus or cumulonimbus.[3] The ubiquitous nature of cirrus clouds can contaminate the aerosol optical depth retrievals, therefore to obtain accurate aerosol information on a large scale, this cirrus effect must be accurately accounted for. In South America, more specifically in Brazil, these questions are very important and need to be answered as the data almost do not exist, as the majority portion of Brazil lies whithin tropical and sub-tropical regions the water-vapor-aerosol interaction plays a distinctive role in cloud formation and radiative transfer processes. We present here measurements of a ground base Lidar (MSP-Lidar) during the period of 2007 at São Paulo, Brazil (23^o33'S, 46^o44'W). For this period high altitude cirrus were frequently observed with a lidar system in a suburban area of the metropolitan area of the city of São Paulo to provide the vertical profile of cirrus clouds at 532 nm up to an altitude of 7-15 km, as well as the cloud optical depth, and their morphological features as base and top of this cloud. In such a way, the authors had compared preliminarily the detection of cirrus clouds by backscatter lidar measurements with the AERONET data, which are extremely novel in Brazil. The radiosonde launches provided by the weather service in São Paulo provide temperature profiles twice per day and thus allow a preliminary characterization of this type of clouds. These first comparisons give an interesting insight about the characterization of cirrus clouds in the region where the data, as mentioned before, are poor or do not exist. These clouds often extend to more than 1000 km horizontally and persist up to a few days[6] and thus allow a extended time "window" to be compared with data from CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder)[7,8] that are used to study the occurrence of cirrus and their optical properties. Also measurements of stratospheric aerossol in comparation with cirrus clouds were performed with the mobile lidar system aboard the German research vessel Polarstern,[9] in this paper it was made a remark that the tropopause was not clearly marked in the aerosol profiles measured in the tropics, and the authors explained by assuming the source of the stratospheric aerosol was in the troposphere and ascended by a large scale driven radiative heating.

2. INSTRUMENTATION

2.1 GROUND INSTRUMENTS: LIDAR AND SUNPHOTOMETER

A ground-based elastic backscatter lidar system (MSP-Lidar, São Paulo, Brazil) has been recently developed in the Laboratory of Environmental Laser Applications at the Center for Laser and Applications (CLA) at the Instituto de Pesquisas Energéticas e Nucleares (IPEN). The lidar system is a single-wavelength backscatter system pointing vertically to the zenith and operating in the coaxial mode. The light source is based on a commercial Nd:YAG laser (Brilliant by Quantel SA) operating at the second harmonic frequency (SHF), namely at 532 nm, with a fixed repetition rate of 20 Hz. The average emitted power can be selected up to values as high as 3.3 W. The emitted laser pulses have a divergence less than 0.5 mrad. A 30 cm diameter telescope (focal length f = 1.3 m) is used to collect the backscattered laser light. Besides the lidar measurements a co-located CIMEL aerosol measurements[10] were performed to determine the AOT values at several wavelengths in the visible spectrum and thus to enable the assessment of the aerosol extinction values at the same spectral region.[11]

2.2 CALIPSO OVERPASSES OVER SÃO PAULO

The CALIPSO satellite overpasses São Paulo about 5 to 6 times per month and the closest distance between CALIPSO ground-track and MSP-Lidar system site varies in a range of 44 km to 100 km. Given that, the strategy chosen was to carry out coordinated measurements 2 hours centered in relation with the time which the satellite reaches the closest distance to the Lidar site. We usually give special attention to the June-September period (so-called Brazilian dry season) when most of the days have poor dispersion conditions and long distance transport are more frequent. On the other hand, during the October-February period these correlative measurements were less frequent, mainly due the occurrence of the precipitation over the lidar site at São Paulo and therefore making the measurements operationaly unavailable. In 2007 there were 47 overpasses over São Paulo in the 40 and 100 km distance range.

2.3 GOES-10 OBSERVATIONS

GOES is a geostationary satellite of 5 spectral channels a visible one (0.55-0.75 μm), three infrared channels (3.8-4.0 μm, 10.2-11.2 μm, 11.5-12.5 μm) and the channel of water vapor (6.5-7.0 μm).[12] In the visible channel the resolution is 1 km. In the Infrared channels the resolution is of 4 km. For this study we used information of ch4 (10.2-11.2 μm) and ch5 (11.5-12.5 μm) each one with 15 minutes of data.

3. METHODOLOGY

Optical depth is one of the cirrus radiative properties usually determined from lidar signals.[13,14] The cirrus cloud optical depth τ is defined through a single scattering assumption, given by:

$$\tau_c = \int_{z_{base}}^{z_{top}} \alpha_c(z')dz' \tag{1}$$

where $\alpha_c(z')$ denotes the particle volume extinction coefficient at altitude z; z_{base} and z_{top} are respectively the base and top of the cloud. We use the methodology described in Cadet[14] to determine preliminary the characteristics of cirrus cloud.

3.1 Molecular Method

The Molecular Integration Method[14] was used to estimate the optical thickness from elastic lidar signals. The total Rayleigh-scattering cross section per molecule (in units of squared centimeters) was derived using the method described by Bucholtz[15] as the total Rayleigh volume-scattering coefficient as a function of wavelength. The lidar integrated backscatter γ is given by equation found in Platt:[13]

$$\gamma = \int_{z_{base}}^{z_{top}} C_s dz \tag{2}$$

where C_s is the normalized lidar signal on the molecular signal in a particle-free region just below the cloud base, z_{base} and z_{top} are the base and the top of cloud respectively.[14] By changing variables and performing the integration, γ becomes:

$$\gamma = \frac{\kappa}{2\eta}[1 - e^{-2\eta\tau_\nu(h)}] \tag{3}$$

From equation (3), τ_ν can be written as (4) being the visible optical thickness, κ is the ratio of visible backscatter coefficient (per 4π sr) to visible extinction coefficient, and η is the ratio of apparent experimental visible extinction coefficient to true visible extinction coefficient.

$$\tau_\nu = -ln[1 - 2\frac{\eta}{\kappa}\gamma]\frac{1}{2\eta} \tag{4}$$

4. RESULTS AND DISCUSSION

4.1 Cirrus Occurence and Data Availability

During the period of 2005-2007, daily measurements of cirrus clouds were performed ($\approx$ 4 to 8 hours), by the lidar system, without any occurrence of precipitation and other events that could compromise the data. In totally it was possible to detect 107 days with cirrus clouds over 261 measurements (Figure 1). The cirrus cloud existence above 7 km is provided with a resolution of 15 and 30m. The annual cirrus occurrence frequencies are calculated from the number of cirrus occurrences divided by the total number of measurements. The Figure 1 shows the variation of cirrus clouds detection by MSP-Lidar system. For 2005 cirrus clouds are observed at 23 of 47 measurements days. For the next year, in 2006, the occurrence of cirrus clouds was detected at 36 of 67 measurements. For 2007 we can observe the most detection of cirrus clouds by MSP-Lidar system, 79 of 150 measurements. In the two first years, the MSP-Lidar system was being put to an operational regime and fewer observations were being carried out. During 2006 shows about 100% of occurrence of cirrus clouds detection in February and March, 1 and 4 days respectively (detection versus measurement by MSP-Lidar system). For the same months, the year of 2007, gives a better representation of cloud frequency cirrus with 4 of 13 and 6 of 14 measurements, respectively.

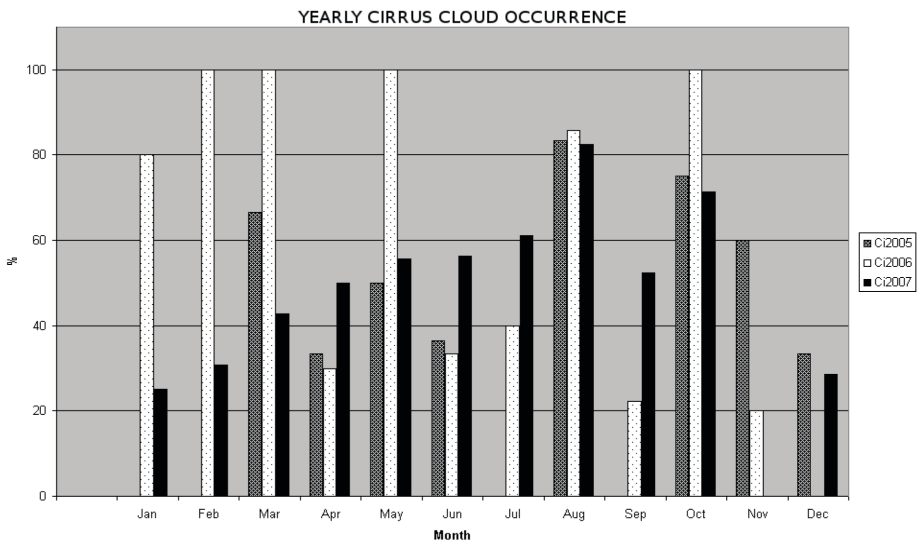


Figure 1: Yearly cirrus clouds occurrence detected by the lidar system in São Paulo.

The measurements and detection of cirrus clouds grow up with the onset of winter (June through September), as the events of precipitations are in general less frequent (driest season at São Paulo), therefore we have done most of our measurements with our lidar system. In the wintertime São Paulo city presents a cirriform cloudiness formation that can be associated with strong cold fronts or sub-tropical jets. We can see in the Figure 1 the relation between the sazonality and frequency of cirrus clouds. Therefore, there is an indication the maximum cirrus cloud occurrence is observed in August and it decreases during the corresponding months spring and summertime, mainly October through May the following year. This sazonal signature is also observed between 2005-2007, in Figure 2, as measured day frequency and cirrus cloud detection is higher during the 2005 - 2007 period. In total 36 days are observed which correspond to a figure about 80% and it minimus reaches 9 days and the fraction is about 55%, in January and with less events during November and December, about 30%. In Table 1 we show there was concomitance with either CALIPSO, GOES-10 overpasses with the ground based lidar in São Paulo and also the cross-checked data from AERONET sunphotometer level 2.0 data. In this table a relation ρ was established as a “flag” ratio between the number of days that an overpass/observation by CALISPO/GOES-10 and an event of cirrus detection by the lidar occurred. Thus a $\rho = 0$ value describes the absence of data or measurement of cirrus clouds by both space based instruments while it was observed by the

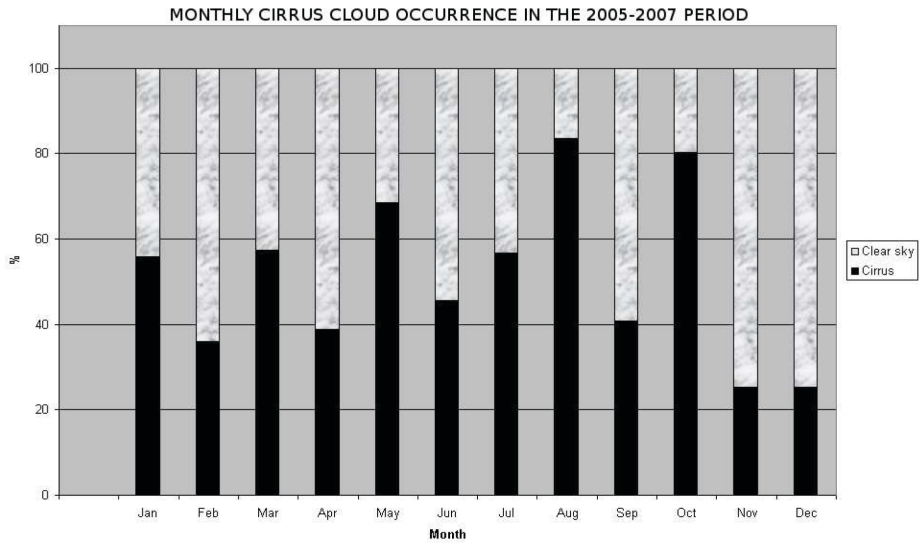


Figure 2: Monthly cirrus clouds occurrence detected by the lidar system in São Paulo summed over the entire 2005-2007 period.

lidar, meanwhile a $\rho = 1$ flag means at least one space based and the lidar ground systems detected cirrus clouds. The ρ flag values mean for the AERONET and lidar values correspond to ratio of the number of days between the 2 systems in which $\rho = 0$ meant the sunphometer was not operational or cloudy conditions were present and $\rho = 1$ as the event when cloud free condition were atributed as the lidar detected the presence of cirrus clouds.

Table 1: Table of the comparison of the lidar-detected cirrus cloud number of days with those retrieved by CALIPSO/GOES-10 and Level 2.0 AERONET systems in 2007

Month	Lidar	Cirrus Lidar	CALIPSO	GOES-10	AERONET
	Total/mo. in days	$0 < \rho < 1$			
January	4	0.25	0	0	0
February	13	0.31	0.25	0	0
March	14	0.43	0.33	0	0.17
April	12	0.50	0	1	0
May	9	0.55	0.20	1	0.40
June	16	0.56	0.33	1	0.89
July	18	0.61	0.18	1	0.55
August	23	0.83	0.16	1	0.89
September	21	0.53	0.18	0	0.73
October	7	0.71	0.20	0	0.80
November	6	0	0	0	0
December	7	0.29	0.50	0	0
Total Cirrus	79	1	0.20	0.42	0.54
Total Measured	150	0.53	0.11	0.22	0.29

4.2 Microphysical Property Retrieval: an example

In order to obtain these results for this day we had first to run a statistical analysis to select an OD time series for 11 Jun 2007 based as seen in Figure 3. The horizontal lines represent the biweight means for each of the seven segments defined as the change-point, defined as: given a sequence of values the change-point is located where all of the values up to and including this "point" share a common statistical distribution and after it the following points or group of them share another point with the same features.[16] In the plot we have calculated a new OD for each segment and thus had the groups of lidar profiles defined. In each segment we were able then to follow the procedure described above and obtained a set of parameters given in Table 2.

In the Fig. 1, the normalization region was chosen between 8.6 - 10.4 km with the cloud base at 8.6 km. The last step before evaluating the optical depth is to find another particle-free region above the cloud top to calculate the attenuation of the lidar signal. In the cases that more than one cloud was present we have performed the calculation separately for each cloud. The results show a lot of consistance when compared to one another regarding the application of the MI Method[14,17] used to estimate the optical thickness from elastic lidar signal. The values of η and κ were 0.37 and 0.25, respectively and taken from the literature.[13] In Figures 4, 5(a) and 5(b) we show an illustration of the MI method being applied to the 14:24 - 14:49 segment. The grey solid curve in Fig. 4 corresponds to the simulated molecular profile calculated using radiosonde data. A polynomial fit, black dotted line, was adjusted between the real signal and the evaluations. The first step in determining τ_ν using this method consists of normalizing the lidar signal to obtain the molecular signal in a particle-free region just below the cloud base and then after it as the grey dotted line.

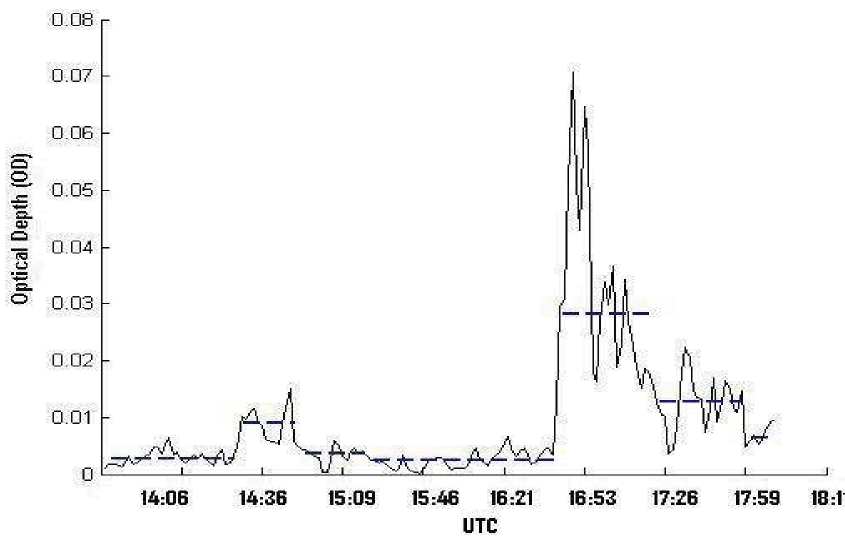


Figure 3: Time series of day Optical Depth (OD) from MSP-Lidar data at 11 June 2007. The horizontal lines represent the biweight means for the seven segments defined by the change-point.[16,18]

4.3 CALIPSO comparison

The CALIPSO satellite overpasses São Paulo about 5 to 6 times per month and the closest distance between CALIPSO ground-track and MSP-Lidar system site varies in a range of 44 km to 80 km. The measurements are conducted then within 2 hours in relation with the time which the satellite reaches the closest distance to the lidar site. For a quantitative correlation we used the Level 1 products of total attenuated backscatter coefficient at 532 nm with 5 km of horizontal resolution and took the lidar backscatter signal data by applying the appropriate correction in such way the attenuated backscatter signal is obtained.

Based on the results above we realize that these preliminary results show the lidar cirrus dataset is able to penetrate thick cirrus, detailing their vertical structures base and top of the cloud, optical depth and κ parameter

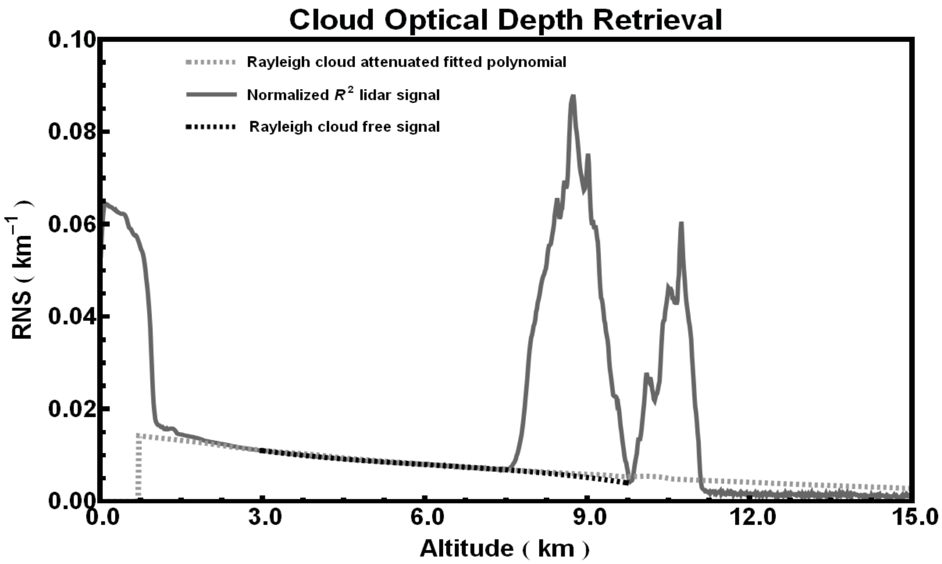
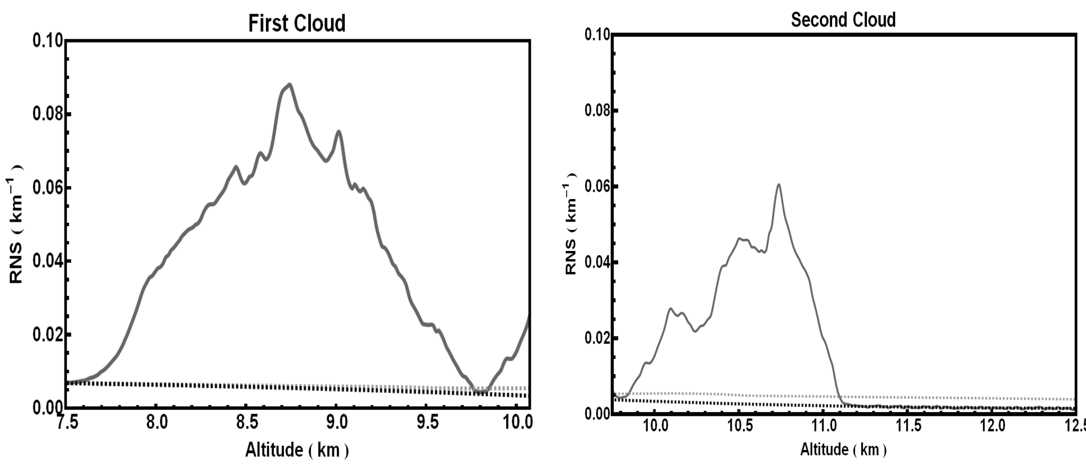


Figure 4: Range corrected signal with the applied molecular its the polynomial fitting on 11 June 2007, segment 14:24 14:49 (GMT); $Z_{base} = 7.7$ km, $Z_{top} = 9.8$ km, $\Delta z = 2.1$ km, $OD = 0.255$ and $\gamma = 0.089$.



(a) First Cloud in the $14:24 - 14:49$ segment. (b) Second Cloud in the $14:24 - 14:49$ segment.

Figure 5: Range corrected signal with the applied molecular its the polynomial fitting on 11 June 2007, segment 14:24 14:49. Their optical and geometrical properties are given in Table 1.

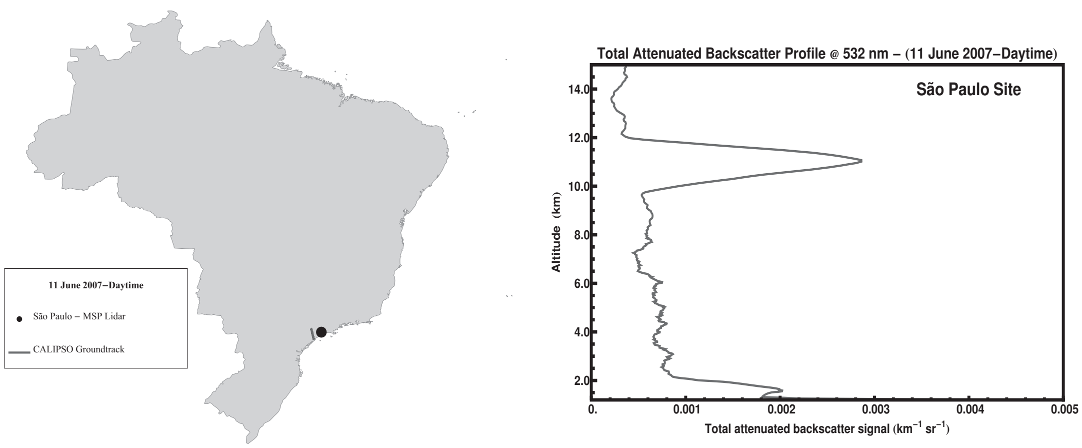
(related to the lidar ratio). This is first step towards the establishment of a cirrus climatology by ground-based measurements in this important portion of the tropical zone. This will allow us to make comparison with other cloud climatologies as those carried in Reunion Island (21 S, 55 E).[19]

5. CONCLUSIONS

We have performed a lidar datset comparison with others datasets of cirrus measurements to start a procedure towards the climatology of cirrus clouds over São Paulo, Brazil. From a ground based lidar backscatter profiles at 532 nm, and eventually 355 nm, we have retrieved the cloud optical depth (COD) as well as the high of base and top of the clouds, we have also established a frequency assessment for a period of 4 years, namely 2005-2008. For the COD calculation we have considered the parameters κ and η based on a previous paper in the literature. As η depends on the multi-scattering "inside" the cloud (mainly angular scattering property

Table 2: The molecular Integration Method (IM)[14,17] was used to estimate the optical thickness from elastic lidar signal. For this calculation we have chosen $\eta = 0.37$ and $\kappa = 0.25$.[13] The resulting attenuated backscatter γ and OD are given as well for a single or a pair of clouds.

Time (GMT)	1^{st} Cloud					2^{nd} Cloud				
	Z_{base} (km)	Z_{top} (km)	Δz (km)	γ	OD	Z_{base} (km)	Z_{top} (km)	Δz (km)	γ	OD
13:27 - 14:24	8.0	9.5	1.5	0.006	0.017	9.8	11.3	1.5	0.043	0.119
14:24 - 14:49	7.7	9.8	2.1	0.089	0.255	9.8	11.3	1.5	0.037	0.119
14:49 - 15:17	7.7	9.9	2.2	0.015	0.040	9.8	11.1	1.3	0.052	0.144
15:17 - 16:39	8.2	9.0	0.8	0.002	0.002	9.0	11.2	2.2	0.038	0.105
16:39 - 17:19	7.5	11.0	3.5	0.259	1.959	n/a	n/a	n/a	n/a	n/a
17:19 - 17:58	8.5	10.7	2.2	0.175	0.988	n/a	n/a	n/a	n/a	n/a
17:58 - 18:11	8.8	10.5	1.7	0.113	0.333	10.5	11.0	0.5	0.007	0.020



(a) CALIPSO trajectory on June 11, 2007.

(b) 300-shot averaged total attenuated backscatter profile.

Figure 6: Cirrus cloud detection with CALIPSO on June 11, 2007.

dependent) and κ is related to the field of view of the collecting system as well the cloud density, a new set of values have been obtained for each cirrus cloud segment given within a given time period in order to retrieve a different COD. In addition the measurements from Aerosol Robotic Network (AERONET), the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and GOES-10 observations were used in our comparison of a wide range of cloud types. According to the preliminary results shown, the lidar dataset is being a helpful tool in establishing not only the optical properties but also the cirrus clouds microphysics starting by a method based on the attenuated molecular signal before and after the cirrus cloud. Besides it is important to make lidar measurements with a sun photometer as the lidar can distinguish between cirrus clouds and aerosols layers and determine their height, optical and geometrical thickness and thus eliminate possible ambiguities that might arise from other type of datasets as the ones obtained by radiometer and photometers that are ground, airborne or satellite based.

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