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Characterization of cirrus clouds in central Amazon (2.89ºS, 59.97ºW): Firsts results from observations in 2011

Caracterización de nubes cirros en la Amazonia central (2.89ºS, 59.97ºW): Primeros resultados de observaciones en 2011

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ABSTRACT:

In 2011 a UV Raman-Lidar station become operational in the central Amazon region. The instrument is installed 30 km up-wind from Manaus-AM and remotely senses the troposphere using a 95 mJ Nd-Yag laser at 355 nm. Receiving optics consists of a cassegrain telescope with 400 mm and 4000 mm focal length. During the first year of operation, a narrow field of view was used to allow a reasonable signal to noise ratio near the tropopause. This study focuses on the characterization of tropical cirrus clouds observed during the first year of operation (February to December 2011). A cloud detection algorithm developed by Barja and Aroche (2001) was adapted for this system and used to determine the cloud base and top heights, and cloud thickness. The method based on the lidar transmittance factor was used to derive the cirrus optical depth. The occurrence of cirrus clouds is about 63% of the total observation time, and these are located between 10 and 16 km height typically. This result agrees with those derived by Sassen *et al* (2008) from Calipso data. We also found that around 26% of all cirrus were subvisual cirrus (τ<0.03), 43 % were thin cirrus (0.03< τ<0.3) and 31% were cirrus stratus (τ>0.3).

Key words: Cirrus, Clouds, Climatology.

RESUMEN:

En la región central de la Amazonía, en el año 2011, se instaló una estación lidar. Se encuentra ubicado a 30 km de Manaos, estado Amazona, Brasil, en la dirección de donde proviene el viento. El instrumento para medir la troposfera a distancia emplea un láser Nd-YAG, con potencia de 95 mJ a la longitud de onda de 355 nm. La recepción es realizada con un telescopio de Cassegrain con 400 mm de diámetro y 4000 mm de distancia focal. Durante el primer año de mediciones se trabajó con un campo de visión estrecho permitiendo un valor razonable de la relación señal ruido cerca de la tropopausa. El presente estudio se enfoca en la caracterización de nubes cirros tropicales observadas durante el primer año de operación (Febrero a Diciembre de 2011). Se adaptó para las condiciones de este sistema lidar el algoritmo de detección de nubes desarrollado por Barja and Aroche (2001). Éste fue empleado para determinar las alturas del tope y la base, y espesor geométrico. Para la determinación del espesor óptico de nubes cirros se empleó un método basado en el factor de transmitancia de la señal lidar. La ocurrencia del tipo de nubes cirros medida con lidar es cercana a 63 % con respecto al tiempo total de observación. Estas se encuentran ubicadas entre 10 km y 16 km de altura. Los resultados encontrados concuerdan con los reportados por Sassen *et al* (2008) empleando datos de lidar CALIOP a borde de satélite CALIPSO. También es resultado del presente trabajo que cerca del 26 % de los cirros fueron clasificados como cirros subvisibles (τ <0.03), el 43 % como cirros delgados (0.03< τ<0.3) y el restante 31% como cirros estratos (τ>0.3).

Palabras clave: Cirros, Nubes, Climatología.

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1. Introduction

Cirrus clouds can significantly alter the radiation balance of the atmosphere, affecting the climatc system from weather to climate change timescales [1]. They are found near the tropopause and are formed mainly by non spherical ice crystals. Despite being relatively transparent to solar radiation (optical depth < 3.0), they are opaque to the infrared radiation that would be lost to space, and thus have a positive radiative forcing [2]. The global cirrus cover has been estimated to be about 20-25% but their occurrence frequency can be more than 70% over the tropics [3-5].

The characterization of the cirrus macro and microphysical properties are very important for climate models. The parameterization of cirrus clouds radiative effects, such as the albedo, transmittance, reflectance and emissivity effects, that are keys quantities to evaluate the radiative balance, are based on the density and size of ice particles, integrated ice water path (IWP) and the optical depth. Those are related to the base and top height, thickness, temperature and other optical properties. So, the lidar systems are powerful tools to study cirrus cloud, measuring with high time and special resolution. In this paper, we present the first results from the first ground based characterization of cirrus clouds over the amazon region, determining the cirrus base, tope and maximum backscattering height, thickness, optical depth and temperature.

2. Data and methods

In 2011 a UV Raman-lidar station become operational in the central Amazon region, installed 30 km up-wind from Manaus-AM (2.89ºS, 59.97ºW). It uses a 95 mJ Nd-Yag laser at 355 nm and 10 Hz repetition rate. Detection system includes an F/10 cassegrain telescope with 4000 mm focal length and photomultiplier

tubes with analog and photon count capabilities. Vertical resolution is 7.5 m and typical time resolution is 1-min. The system operates almost full time, being closed only between 11am and 2pm local time due to direct sun light. To retrieve macro and microphysical properties of cirrus clouds, a narrow field of view and a 5-min time resolution were used to allow a reasonable signal to noise ratio near the tropopause. We define the signal-to-noise ratio as the ratio between the signal and its standard deviation. In this paper, we consider as good signal-to-noise profiles the ones in which the signal is 3 times larger than its noise in the region of occurrence of cirrus clouds. Detailed description of the Raman-Lidar system can be found in [6].

Figure 1 shows for each month the total number of 5-min profiles measured (blue), the number of profiles with a good signal-to-noise ratio (green) and the number of profiles in which the presence of cirrus clouds was detected (yellow) during year of 2011. In total, 23335 profiles were obtained, 61.4% of these had a good signal-to-noise ratio and cirrus clouds were detected in 63.1% of these good profiles. In March, April, May and June no measurements were made due to problems in the automatic hatch. In addition to the lidar data, vertical profiles of temperature and pressure were obtained by radiosondes launched at 0 and 12 UTC from Ponta Pelada Airport, located at 59.98ºW, 3.14ºS approximately 28.5 km south of the experimental site. Thus, we used the atmospheric profiles data from radiosondes which was launched at an instant in time closer to the moment of the lidar measurement.

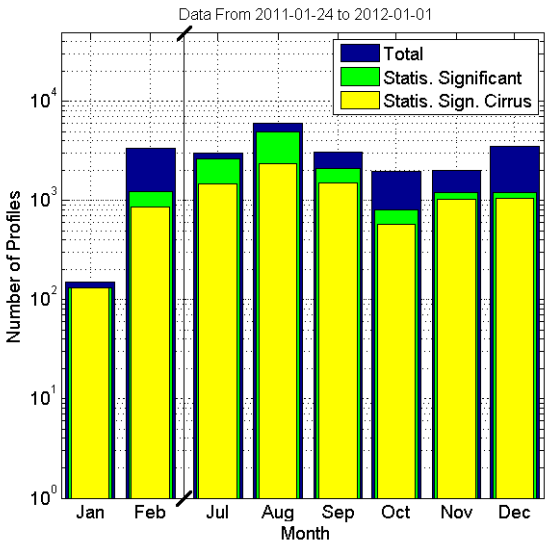

Fig. 1. Monthly number of 5-min profiles measured in 2011, the total in blue, the profiles with good signal-to-noise ratio in green and the profiles which was detected cirrus clouds in yellow.

To analyse this large amount of data, an automated algorithm for the detection of cirrus clouds was developed having as starting point an algorithm previously described in the literature [6,7]. Our algorithm determine the cloud base, top and maximum backscattering heights and cloud thickness. The algorithm working principle is the monotonically decreasing intensity of a lidar signal with altitude in a clear atmosphere. When a cloud appears in the atmosphere, the signal has a significant abrupt increment. The automated algorithm steps are:

1. Compare the raw signal in each bin with its neighbors and calculate all local minima and corresponding maxima, grouping them in pairs;
2. Apply a 3-point moving average to the raw signal and calculate all local minima and corresponding maxima of the filtered signal;
3. Exclude those min/max pairs that are not found at the same time in the raw and filtered signals;
4. Apply statistical test and select min/max corresponding to clouds those pairs that the signal value at maxima is incompatible with the expected molecular signal of a clean atmosphere at that altitude level;
5. Select the cloud base height as the first minimum found when searching upwards and select the apparent cloud top height where the raw signal value is equal or less than signal value at cloud base and its slope is compatible with the expected molecular signal;
6. Find the height of maximum signal between base and top, i.e., the maximum backscattering height, and take note of the intermediary minima as they indicate sub-layers of the same cirrus cloud;
7. Repeat steps 5-7 for the region above cloud top to identify other cirrus layers.

The automated algorithm is robust and fast, allowing us to make a high time resolution analysis of cirrus clouds properties. Each one of

the 5-min profiles was at least quickly visually checked in order to avoid obvious mistakes in the values obtained by the automated algorithm. The temperatures of the base, top and maximum backscatter from clouds and other temperature levels were obtained from nearest radiosonde. Following what is done by [8], a detected high cloud is classified as a cirrus cloud if the layer is in a temperature level equal or less than -25ºC, temperatures generally found above 8 km in our experimental site.

Once the base and top of cirrus clouds are detected, the optical depth is obtained by measuring the attenuation of the elastic signal due to cirrus clouds layers. Starting from the elastic lidar equation [9], the ratio of the range corrected signal at the top and at the cloud base is given by:

$$\frac{S(z_t)}{S(z_b)} = \\ = \frac{\beta(z_t)}{\beta(z_b)} e^{-2\int_{z_b}^{z_t}\alpha_p(z')dz'} e^{-2\int_{z_b}^{z_t}\alpha_m(z')dz'}, \quad (1)$$

where z_b and z_t are the base and top heights, $S(z) = P(z)z^2$ is the range corrected signal, $\beta(z) = \beta_m(z) + \beta_p(z)$ are the total, the molecular and particle volumetric backscattering coefficient, and $\alpha(z) = \alpha_m(z) + \alpha_p(z)$ are, respectively, the total, molecular and particle volumetric extinction coefficients. Due to the high altitude of cirrus clouds, we can consider that the amount of aerosols is very small in the atmospheric layer below the cirrus base and above the cirrus top [10], i.e., for $z < z_b$ and $z > z_t$ we have $\alpha_p(z) \approx 0$ and $\beta_p(z) \approx 0$. Thus, the transmittance factor of the lidar equation due to cirrus cloud (T^{cirrus}) is given by:

$$T^{cirrus} = e^{-2\int_{z_b}^{z_t}\alpha_p(z')dz'} = \\ = \frac{S(z_t)}{S(z_b)}\frac{\beta(z_b)}{\beta(z_t)} e^{2\int_{z_b}^{z_t}\alpha_m(z')dz'}. \quad (2)$$

Thus, the optical depth of cirrus clouds (τ^{cirrus}) is obtained by:

$$\tau^{cirrus} = \int_{z_b}^{z_t} \alpha_p(z')dz' = -\frac{1}{2}\ln(T^{cirrus}). \quad (3)$$

The quality of the optical depth determination by this method depends mainly on the lidar signal quality, the determination of extinction and backscatter coefficients, and the determination of geometric boundaries of the cirrus cloud. Because we have twice a day the profiles of temperature and pressure given by the radiosondes, the volumetric backscattering and extinction profiles can easily be derived following the methodology in [11]. As the method is based on the ratio of the lidar signal from below and above the cloud, an overestimation of z_b or underestimation of z_t may result in a large error in the determination of the cirrus optical depth. On the other hand, using a value lower than the true base height or a value higher than the true top heigth, in other words, $z'_b = z_b - \delta z$ and $z'_t = z_t + \Delta z$ with δz, $\Delta z > 0$, will not necessarily change the value of the optical depth, because, if we have a clean air layer above and below the cloud, then:

$$\int_{z_b-\delta z}^{z_t+\Delta z} \alpha_p(z')dz' = \int_{z_b}^{z_t} \alpha_p(z')dz' = \tau^{cirrus}. \quad (4)$$

as $\alpha_p^{cirr} = 0 \; \forall \; z < z_b$ and $z > z_t$. When the signal is completely attenuated by the cirrus cloud, i.e., when the transmission factor goes to zero ($T^{cirrus} = 0$), it is impossible to obtain the true height of cloud top and true optical depth. In such cases, the apparent values of the top and optical depth are called $z_{t,appar}$ and τ_{appar}^{cirrus} representing lower limits for these quantities.

3. Results

Figure 2 shows the average diurnal cycle of cloud cover obtained from all days of measurement. This frequency of occurrence is directly the fraction of the time that the sky was covered with cirrus clouds of different geometrical and optical characteristics. We can see that a well-defined diurnal cycle with a maximum value in the afternoon and maintaining a high frequency of occurrence during the night, decreasing during the day to approximately 40% at 10 am.

After determining the macrophysical characteristics, the transmittance method described in the previous section was applied to the determination of the cirrus clouds optical depth. Figure 3 shows an example of a profile

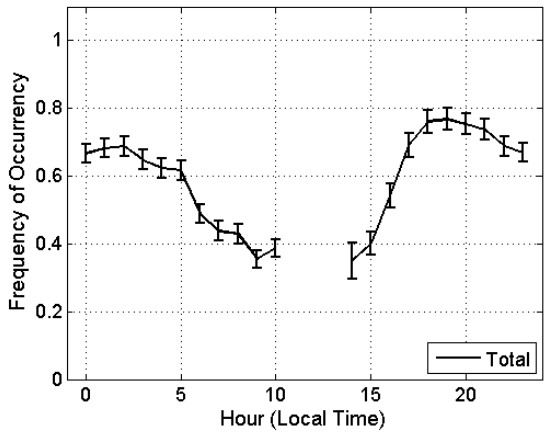

Fig. 2. Mean diurnal cycle of the cirrus frequency of occurrence. The error bars represents the standard deviation.

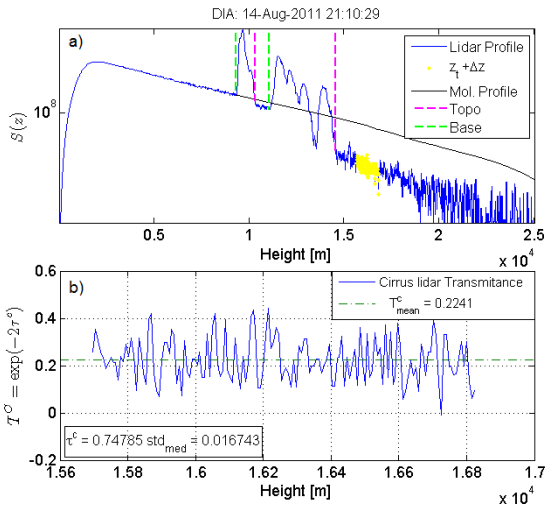

Fig. 3. Example of a cirrus clouds detected with the automated algorithm. (a) The RCS with the base and top heights (green and magenta dashed lines), the molecular RCS adjusted below the cloud base (black line) and the region above the cloud used to calculate the transmittance. (b) The lidar transmittance factor for this cloud, with the mean value and the optical depth τ^c retrieved with the transmittance method described in this work.

with cirrus clouds and the result of applying the detection algorithms. In Fig. 3(a), the altitude of the base and the top of the cirrus cloud identified by our algorithm are indicated. The black solid line is the molecular range corrected signal adjusted in a layer just below the base of the cirrus cloud. This molecular signal is the signal that would be measured without the presence of the cloud. Thus, the attenuation of the lidar signal due to the two layers of cirrus clouds can be directly seen. The yellow points represent the 150 values $S(z_t + \Delta z)$ that were used to calculate the transmittance of the lidar signal (T^{cirrus}) through Eq. (2) which are shown in Fig. 3(b). The possibility of using data over the top of the cloud prevents error in the determination of the optical depth due to underestimation of the top height improving the accuracy. Thus, after calculating the average value of T^{cirrus}, the cirrus optical depth is obtained from Eq. (3). The transmittance method presented in the previous section and discussed in this example proved to be very robust and easy to implement in an automated algorithm.

The results of cirrus macrophysical and optical properties obtained by our algorithm from lidar data collected in 2011 are shown in Fig. 4. In Figs. 4(a) and 4(b) are the normalized histograms of the base, maximum backscatter and top heights and the thickness of cirrus clouds. We can see that the histograms have only one peak, with mean values of 11.9 km (std=2.1 km) for the base height, 13,6 km (std=2.0 km) for the top height and 1.75 km (std=0.98 km) for the thickness. The mean value of the maximum backscattering height is 12.7 km (std=2.0 km), whit mean temperature in the maximum backscattering height (Fig. 4(d)) of -54ºC (std=16ºC). In Fig. 4(c) it is shown the cirrus clouds optical depth. Following the classification made by [12], our measurements indicate that 26% of all cirrus clouds were subvisual cirrus clouds (τ<0.03), 43% were thin cirrus (0.03< τ<0.3) and 31% were cirrus stratus (τ>0.3). The average frequency of occurrence of cirrus clouds throughout the period of observation was 63% of the time we had measurements with good signal to noise ratio near the tropopause. These results are similar to those obtained by [4] and [5] in global studies using one year of Calipso data. In these studies, the annual frequency of cirrus clouds occurrence over the same region of our experimental site was about 60-65% for [4] and about 50-60% for [5], both very close to what we measured with a ground based instrument. Also, these studies presented a zonal mean distribution of cirrus cloud base and top layers as a function of the latitude. In [4] authors found that the mean base and top height for the 0-10ºS latitude band is about 13.0 km and 14.8 km respectively and in [5] found values about 12.5 km and 15.0 km for

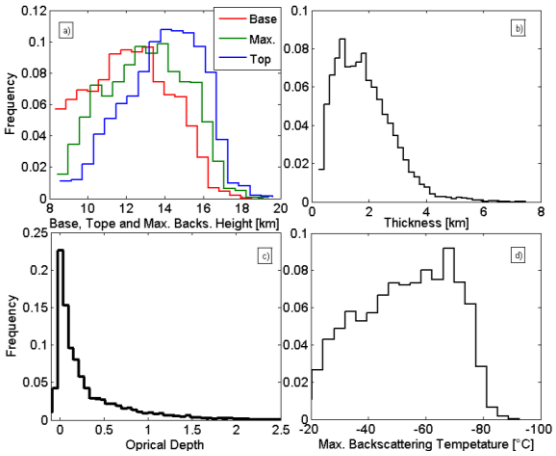

Fig. 4: Normalized histograms with the retrieved macro and microphysical properties of the cirrus clouds: In (a), the base (red), tope (blue) and maximum backscattering (green) heights; in (b) the cirrus thickness; in (c) the cirrus optical depth and in (d) the temperature of the cirrus max, backscattering height.

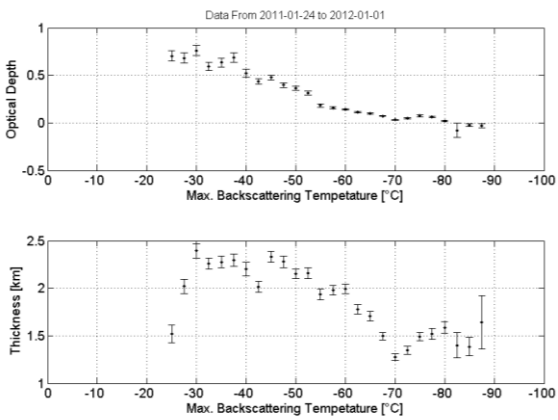

Figure 5: Optical depth and thickness dependence on the temperature of the max. backscattering height of the cirrus clouds for the total number of measurements.

base and top heights in the same latitude band. Again, in close agreement to our findings.

The thickness and optical depth of the cirrus clouds are shown as a function of the maximum backscattering temperature in Fig. 5. Cirrus clouds were found to be thicker between -30ºC and -50ºC, with thicknesses between 2.0 and 2.5 km, getting thinner for colder temperatures –50ºC. The reduction in thickness for warmer temperatures ($\preccurlyeq -30$ºC) needs further investigation. The optical depth has a more clear trend, decreasing smoothly for lower temperatures. Similar results were found by [8] for midlatitude cirrus clouds observed in the south of France (43.9ºN, 5.7ºE).

4. Conclusions

The first characterization of cirrus clouds over the Amazon region from a ground based lidar was performed. The automated detection algorithm showed a good efficiency in detecting both thick and subvisual cirrus clouds. The macrophysical characteristics and optical depths found in this study were consistent with global results based on satellites measurements. The method used to obtain the optical depth proved to be very stable and easy to implement in an automated manner, thus allowing us to study cirrus clouds with high temporal resolution. The next steps in our research include obtaining the backscattering and extinction coefficient profiles of cirrus clouds using the Klett and Raman methods and doing a cluster analysis to classify the cirrus clouds. Our lidar station will continue making measurements continuously in the coming years, and so we will be able to follow the evolution of cirrus clouds in the context of climate change.

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