Cloudiness Characterization in Seville Using Ceilometer Measurements

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Abstract. Laser Ceilometers make use of the elastic LIDAR by emitting signals vertically in the atmosphere and analyzing the profile of the backscattered signal to detect clouds and calculate cloud-base height [1]. Due to the high temporal and vertical resolution, the data provided by the ceilometer is rather useful for solar radiation forecasting or assessing the potential of night radiative cooling of a fluid. To characterize cloudiness, we calculated the cloud occurrence and frequency distribution of cloud-base height in Seville, in a similar way to [2]. Furthermore, we analyze the backscatter signal to obtain a time series, with hourly resolution, of estimated cloud depth and cloud optical thickness that would be useful to determine the effects of clouds on solar radiation and night radiative cooling.

INTRODUCTION

Solar radiation variability has a significant impact in Concentrated Solar Power plant's production [3]. Since cloudiness is the main cause of variability in solar radiation, characterizing the interaction between clouds and solar radiation is fundamental in order to obtain more accurate solar radiation estimations.

Ceilometers provide information that could be used in solar radiation forecasting. They provide information of cloud base height, optical thickness and vertical extension. Besides their significant cost, their high temporal resolution, along with their relatively minimum needs of maintenance suits them as a promising device for a better understanding of the interaction of the solar radiation with the clouds. These results could be used for solar radiation forecasting and night cooling of photovoltaic modules using phase change materials, or the evaluation of night radiative cooling's potential, given that these applications are highly dependent on cloudiness. Ceilometers are also used to determine direct normal irrandiance variation due to the presence of aerosols in the atmosphere [4], and therefore have a great potential in concentrated solar power applications. The existence of a network of meteorological stations that provide ceilometers measurements makes the methodology introduce in this paper widely applicable in the development and operation of solar energy systems. Associations such as EUMETNET and its program E-PROFILE (https://e-profile.eu/#/) provides ceilometer measurements for a number of locations.

To characterize cloudiness in Sevilla, we carry out a similar analysis as in [2]. We analyze cloud occurrence and cloud base height. Furthermore, we develop a novel algorithm that provides estimations of cloud optical depth and the vertical extension of clouds by analyzing the backscatter signal provided by the ceilometer.

Cloud optical thickness is the most important variable in the attenuation effect produced by clouds. It is defined in [5] as:

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$$\tau = \int_0^H \sigma_{ext}\,(z)\,dz$$

Where H is the cloud's vertical extension, z is the vertical distance and σ_{ext} is the extinction coefficient, which represents the fraction of extinguished radiation per thickness unit. The extinction coefficient is not provided by the ceilometer; however, this variable is directly proportional to two parameters: the concentration of the hydrometeors present in the cloud and to the size of them. Given that the intensity of the backscatter signal is also directly proportional to these two parameters, we will use the backscatter signal as an estimator of cloud optical thickness. We have developed an algorithm analyzes backscatter signal in an hourly basis and estimates cloud vertical extension and optical thickness.

METHODOLOGY

We use the cloud base height records to obtain cloud occurrence and calculate monthly mean values for both variables. We also process the backscatter signal to obtain a time series of cloud information in an hourly basis. A threshold for the backscatter signal is imposed for each layer. See table 2. For values higher than said threshold, a cloud is identified. The vertical extension of the cloud is calculated by finding the extension of the values that are higher than the threshold. Then, the cloud optical thickness is estimated by calculating the mean backscatter signal in the time that the cloud is identified.

Database

The dataset used in this study corresponds to one year of measurements obtained by a Lufft CHM-15K Ceilometer from March 2018 to February 2019. This device is located at the meteorological station of the Group of Thermodynamics and Renewable Energy of the University of Seville (37.41ºN, 6.01ºW). The Köppen-Geiger climate classification in Seville is Csa (Typical Mediterranean).

FIGURE 1. Meteorological station of the GTER

The data provided by the ceilometer is stored in daily NetCDF files. These are self-describing, array-oriented and machine-independent files commonly used for sharing scientific data. The measurements are registered with a temporal resolution of 15 s and a vertical resolution of 15 m. Up to three layers of clouds can be detected simultaneously. The ceilometer provides measurements up to 15 km, although it fails to report some clouds at high altitudes, especially in situations when lower, more dense clouds appear at lower heights that absorb the radiation emitted by the ceilometer.

We divide the measurements in three layers:

TABLE 1. Cloud layers and distance above ground

Cloud layer	Distance above ground level (km)
Low	0 – 2
Middle	2 – 7
High	7 - 15

The ceilometer outputs used in this article are:

- Backscatter Signal: The main output provided by the ceilometer is a register of the intensity of the signal backscattered to the instrument as a function of height.
- Cloud-Base Height: A built-in algorithm analyzes the backscatter signal and identifies a cloud base where a sudden increase of the backscatter signal is found.

Cloudiness Estimation

We provide a characterization of cloudiness based on the four following variables:

1. Cloud occurrence: defined in [3] as the relation between the number of cloud records and the total number of records. We calculate daily and monthly values of cloud occurrence, considering the totality of the records. We also distinguish between daytime and nighttime data.
2. Cloud-base height: A built-in algorithm calculates the height of a cloud base by analyzing the backscatter profile. We calculate daily and monthly values of cloud base height. As we did before, we also distinguish between as daytime and nighttime values of cloud-base height.
3. Cloud optical depth and cloud vertical extension: We obtain a time series, with hourly resolution, of cloud optical depth and vertical extension estimation. These estimations are obtained by analyzing the hourly backscatter signal.

The first step of this analysis is the integration of the instantaneous backscatter signal to an hourly resolution. For each height, we obtain the mean backscatter value of each hour. This simplified matrix of backscatter values allows for a faster handling of the data. In Fig. 2 we present the instantaneous backscatter intensity profile. In Figure 3 we present the hourly backscatter intensity profile.

Once the simplified matrix is obtained, we analyze the hourly backscatter signal to obtain estimations of cloud optical depth and vertical extension. The first step to do so is to impose a threshold value for the backscatter signal for each layer. We consider the presence of a cloud when the signal is higher than the threshold value. Said threshold is chosen based in the following procedure: Using the cloud occurrence given by the ceilometer, we classify each layer, for each hour, as cloudy if more than 50% of the registers report the presence of clouds. Once this hourly array is obtained, we empirically find the threshold values that provides the highest agreement between the cloud occurrence given by the threshold method and the cloud occurrence given by the ceilometer. In Table 2 we present the obtained backscatter threshold values for the identification of presence of clouds in each layer.

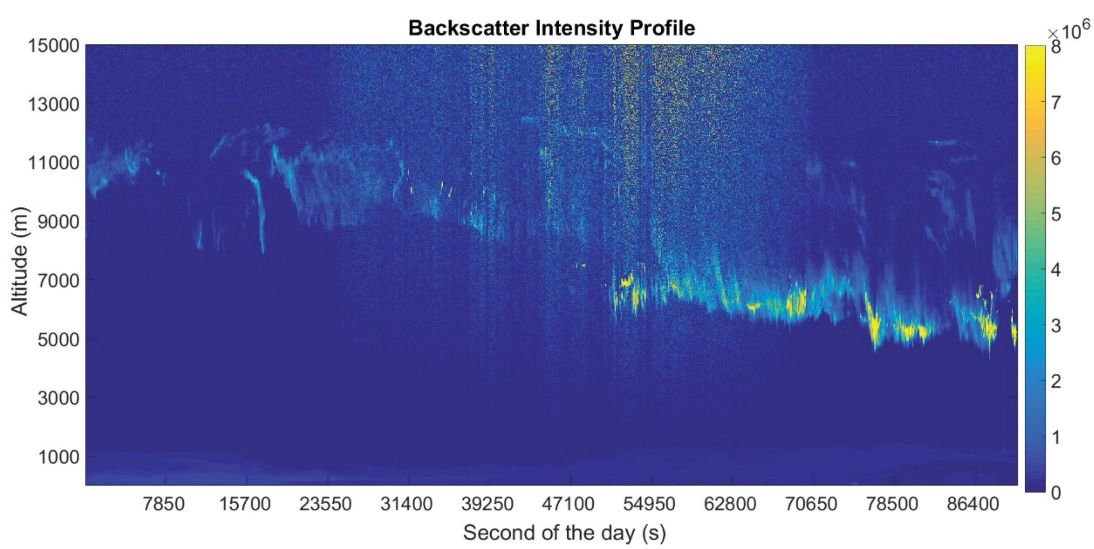

FIGURE 2. Instantaneous Backscatter Intensity Profile, 15 s resolution

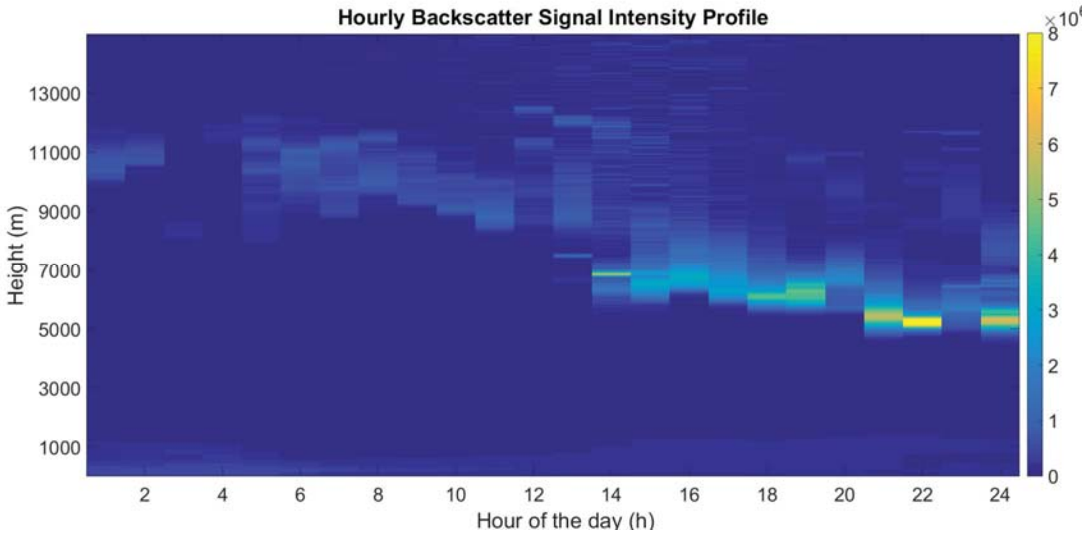

FIGURE 3. Hourly Backscatter Intensity Profile, hourly resolution

TABLE 2. Backscatter threshold values for the identification of presence of clouds in each layer

Cloud layer	Backscatter Threshold ($m^{-1}sr^{-1}$)
Low (0-2 km)	$4.5 \cdot 10^5$
Middle (2-7 km)	$2.5 \cdot 10^5$
High (7-15 km)	$8 \cdot 10^4$

RESULTS AND DISCUSSION

The cloud occurrence is presented in Fig. 4 in a monthly basis and in the three different layers. In Figure 5 we present the total cloud occurrence differentiating daytime and nighttime. The cloud base height is presented in a histogram in Fig. 6. Cloud optical depth and cloud vertical extension are presented in histograms separating by layer in Fig. 7 and 8 respectively. Low layer is represented in blue, mid layer in orange and high layer in yellow.

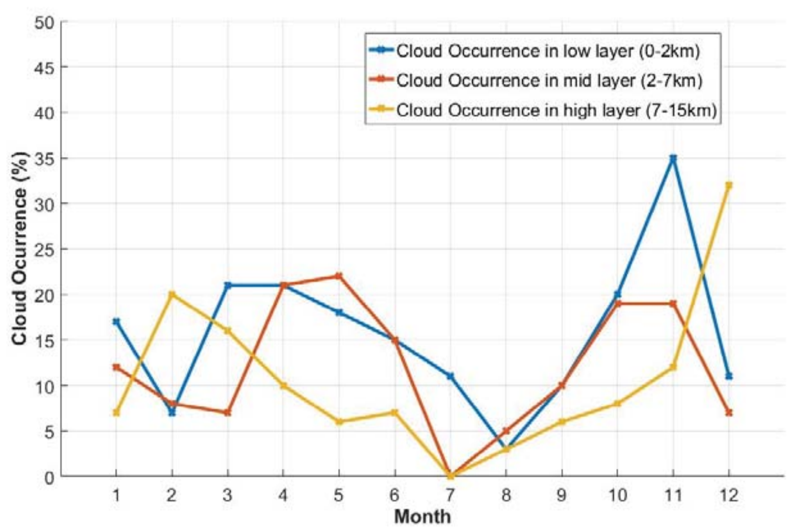

FIGURE 4. Monthly cloud occurrence in each layer

Considering all the analyzed records, cloud occurrence fluctuates around 30 and 40% for most of the analyzed months, except for summer months, where lowest cloud occurrence values are found, with only 10% of the records indicating the presence of clouds. The highest values of cloud occurrence are found in November and December with 70% of registers with clouds.

The results of cloud occurrence for each layer show a predominance of cloud occurrence in the low layer for most of the year. Cloud occurrences of low and mid layer show a similar behavior, while cloud occurrence in high layer is significantly lower for most of the year. February and December are an exception to this tendency, when a maximum in cloud occurrence for the high layer is observed. There are no significant differences between day-time and night–time cloud occurrence, as shown in Fig. 5.

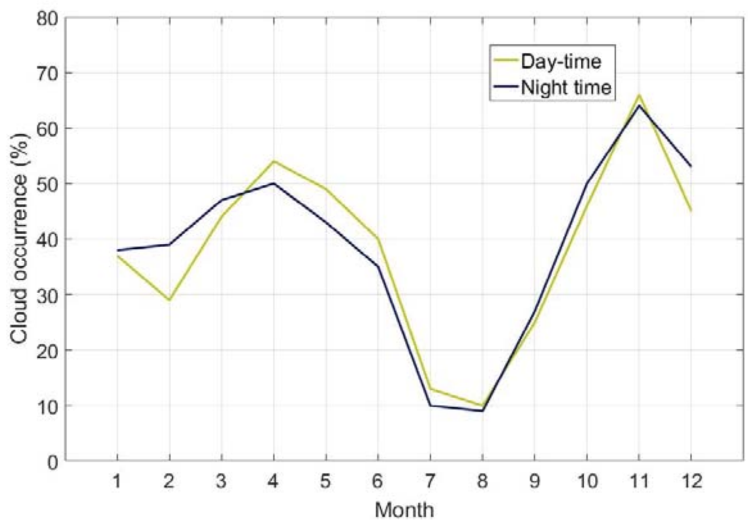

FIGURE 5. Total cloud occurrence during day-time and night-time

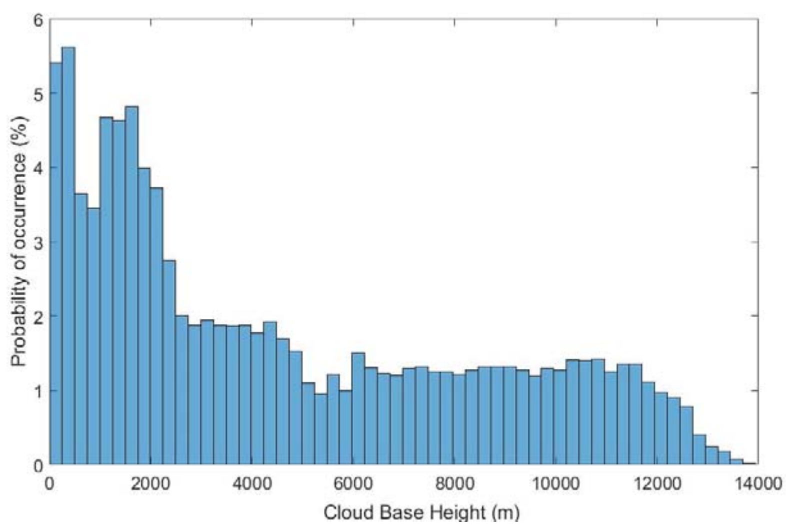

FIGURE 6. Cloud base height histogram

Regarding Cloud-Base Height, we find a that clouds in the low layer (0-2 km) are the most probable, while the bins from 2 to 12 km show approximately the same probability, as it is shown in Fig. 6.

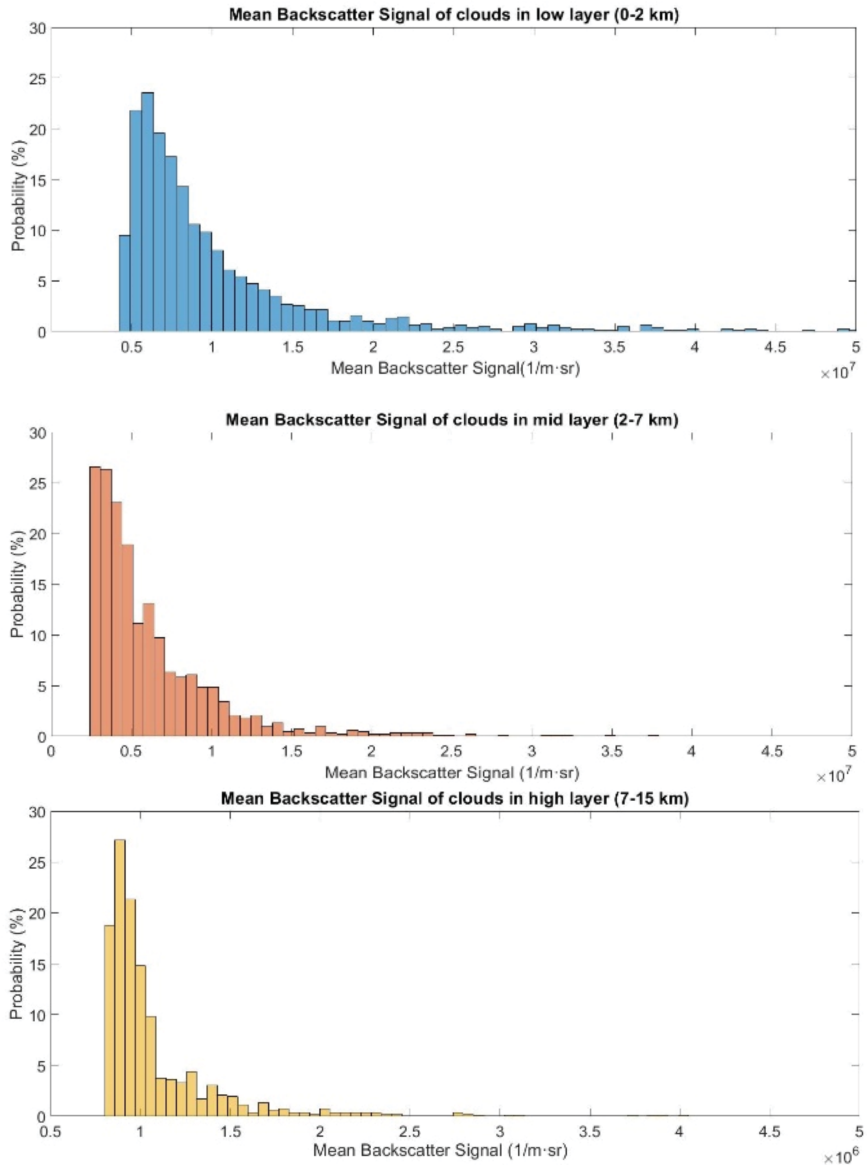

FIGURE 7. Mean backscatter signal in each layer

Clouds in low and middle layers present the highest mean backscatter values. Besides clouds, high mean backscatter values in the low layer are also caused by events of fog and rain. While the mean backscatter values are higher in the low layer than in the middle layer, they are of the same order of magnitude, so we can assume that their attenuating effect of solar radiation is similar. In contrast, the mean backscatter values of clouds in the high layer (7-15 km) are an order of magnitude lower than those in low and mid layer, and therefore we can assume that their attenuating effect is less predominant than clouds in lower layers.

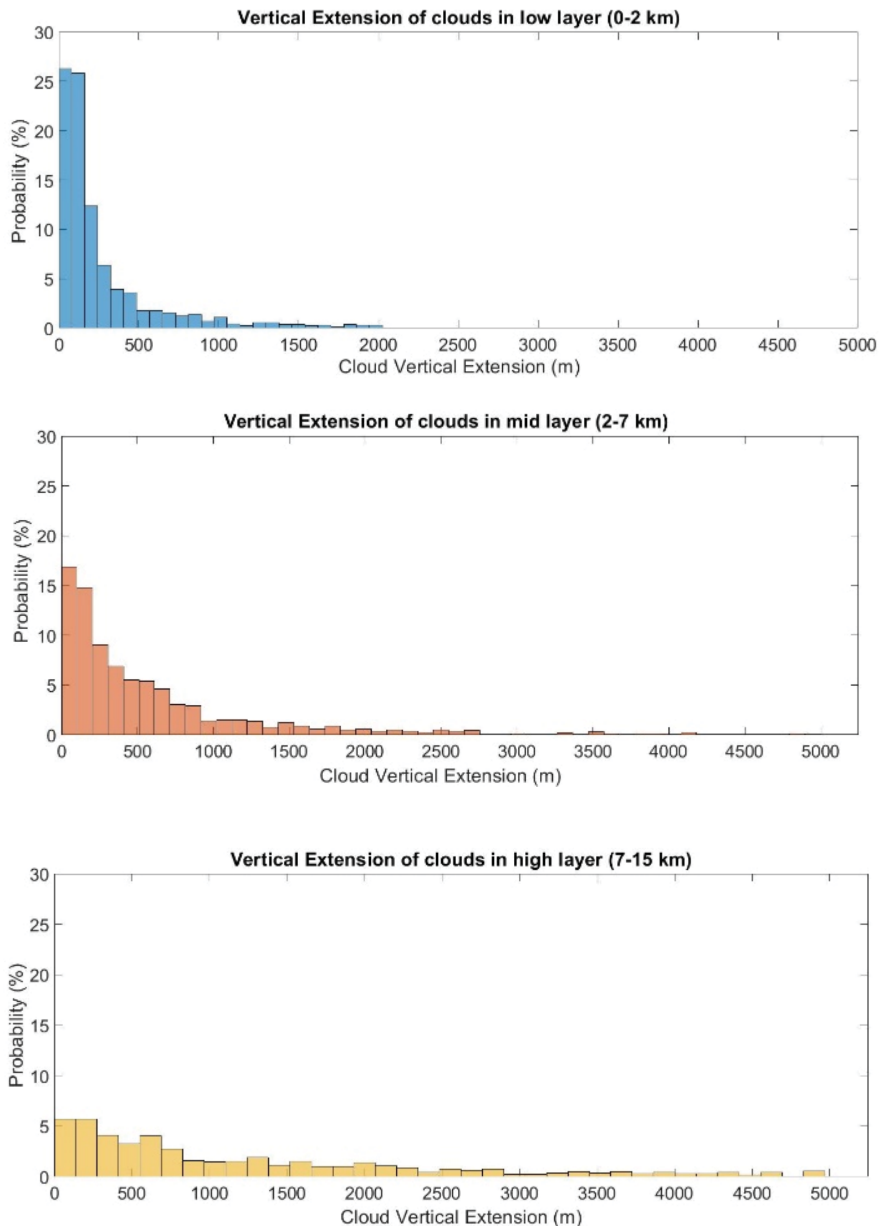

FIGURE 8. Vertical extension of clouds in each layer

Regarding cloud's vertical extension, the tendency shown is quite the opposite to cloud's optical thickness: Clouds at higher altitudes show greater vertical extension than clouds at lower altitudes. Around 40% of clouds in the low layer have a vertical extension under 500 m. For vertical extensions higher than 500 m, the probability of each bin is always lower than 2.5 %. Regarding clouds in the mid layer, while around 62 % of the registers are of clouds with a vertical extension under 500 m, the bins of more than 500 m show. In the mid and high layers, the bins are less concentrated in the lower end of the vertical extension values, and more spread towards higher ones.

CONCLUSIONS

From the results we can conclude that cloud optical depth and vertical extension are mostly dependable on cloud's height, showing little seasonal variation. Moreover, there is no significant differences between day-time and night