Evolution of cloud vertical structure and number of days with cloud detection at Barcelona, Spain

Martí Espinós Sánchez
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.[*]

Advisor: Yolanda Sola Salvatierra

Abstract: Clouds play a very important role in the planet's energy budget as they interact with incoming solar radiation (shortwave) and outgoing terrestrial radiation (longwave). Depending on their characteristics, they can affect the temperature of the Earth's surface. The vertical structure of clouds also affects the accuracy of meteorological and climatological models that allow us to make predictions. Variations in these magnitudes can be a clear indicator of the consequences of climate change. This study examines the temporal evolution of the vertical structure of the first cloud layer and the number of days with cloud detection derived from radiosondes in Barcelona, Spain, from 1998 to 2022. The results obtained show that the cloud base height has decreased by -0.36 m/year, the cloud top height has increased by 0.09 m/year, and the thickness of the clouds has increased by 0.46 m/year. As for the number of days with cloud detection, an increase of 9.12 days per year has been observed.

I. INTRODUCTION

Clouds cover about 67% of the Earth's surface at any given time [1], having a notable influence on many natural processes.They interact with shortwave and longwave irradiances and consequently have large implication in the global radiative budget. In the hydrological cycle, clouds are relevant as their creation and precipitation affect the availability of water in different regions. Moreover, they play an important role in climate feedbacks where variations in their physical and optical properties can accentuate or mitigate the effects of greenhouse gases emissions. Understanding the cloud vertical structure (CVS), i.e., the locations of cloud base and top, the thickness and number of cloud layers are crucial for improving meteorological and climate models.

Clouds reflect part of the incoming solar radiation back into space, which causes the Earth's surface temperature to decrease. At the same time, clouds trap part of the radiation leaving the Earth emitting also longwave radiation, keeping the heat in the atmosphere. The interaction of clouds and radiation partially depends on the CVS. Climate change is affecting these properties and the distributions of clouds. The global increase in temperatures is causing changes in their height, thickness, and geographical distribution [2].

Meteorological satellites employ passive and active sensors to observe the atmosphere and Earth's surface. While these sensors offer global coverage, their accuracy has limitations, especially in capturing variations in the lower level of the CVS. Passive sensors rely on received radiation and, as disadvantages, there is the dependence on solar radiation. Morever, their effectiveness can be reduced at night or by the appearance of aerosols, and other particles that can interfere with the measurements. Active sensors emit radiation at specific wavelengths and measure the backscattered or reflected radiation, offering advantages, such as deeper penetration in clouds and higher resolution but consume more energy and are costlier. Complementarily, ground-based active detectors provide high precision and continuous observations but are limited in deployment and history. Another type of detector that is very important is the radiosonde, since these instruments play a crucial role in providing atmospheric data for weather forecasting and climate research and offer detailed insights not easily achievable by satellite sensors alone. With the help of the data provided by radiosondes, we can better understand the vertical structure of clouds and thus make a more accurate interpretation of satellite data.

This study aims to examine the CVS, i.e., the height of the base, the top, and the thickness of the first cloud layer, as well as the number of days with cloud detection using routine radiosonde data launched twice daily from 1998 to 2022 in Barcelona, Spain. Particularly in this work, an attempt is also made to identify any kind of trend in the CVS.

The paper continues with section 2 where the method and how the clouds have been determined are explained. Section 3 presents the main results. Finally, in section 4, the main conclusions are given.

II. METHODOLOGY

A. Radiosonde observations

Radiosondes used for data collection have been launched from the Faculty of Physics at the University of Barcelona (41.39° N, 2.12° E), Spain. The radiosonde has been launched twice a day, at times close to 12 UTC, from 1998 to 2022. It is worth noting that during this

[*]Electronic address: `mespinsa39@alumnes.ub.edu`

period, two different generations of radiosonde have been used: from 1998 to 2011 Vaisala radiosondes (RS-80, RS-92), which were replaced by Meteomodem M10 sondes in 2011. We were aware that these devices have different sensitivity [3]. However, following the criteria of [4] who only used Vaisala sondes, we have considered that these differences are so small that they do not invalidate the validity of our study.

In this work, we have not been able to study the variations throughout the day or night continuously, as radiosonde launches occur at a low frequency (twice a day), and they remain in the sky for a limited time. Another important factor is that, due to the effect of the wind, the radiosonde changes its location, meaning that throughout the data recording, we may not be exactly above the launch point. When studying the first cloud layer, we have underestimated this effect, assuming that the radiosonde has not deviated too much.

B. Methodology of determining cloud locations by radiosonde data

To carry out this analysis, we have followed a methodology very similar to that described by [4]. It should be noted that all data processing has been carried out by a Python code designed exclusively for this study. One of the main drawbacks of this method has been the large volume of data (25,282 files), that had to be filtered and processed.

Cloud layers form with high relative humidity, so the first step was to calculate the profile of relative humidities. To do this, the vapor pressure was calculated using the dew point temperature provided by the radiosonde. To calculate the saturation vapor pressure, the same expression was used but with the air temperature, also provided by the radiosonde. It is important to note that, to calculate the saturated vapor pressures, we used two different expressions: one with respect to liquid water and the other for ice when air temperature was lower than 0°C [5]. Finally, to obtain the relative humidity: $RH\% = \frac{e(T_d)}{e_s(T)} \times 100$. It is true that the radiosonde also provides the RH value, but we have as it made it more consistent to calculate RH for ice.

Altitude range	min - RH	max - RH	inter-RH
0-2 km	92%-90%	95%-93%	84%-82%
2-6 km	90%-88%	93%-90%	82%-78%
6-12 km	88%-75%	90%-80%	78%-70%
>12 km	75%	80%	70%

TABLE I: Height-resolving RH thresholds, based on [4]. A linear variation betwen values in the altitude rangs has considered.

In this method, three height-resolving relative humidity thresholds were used to determine where clouds form.

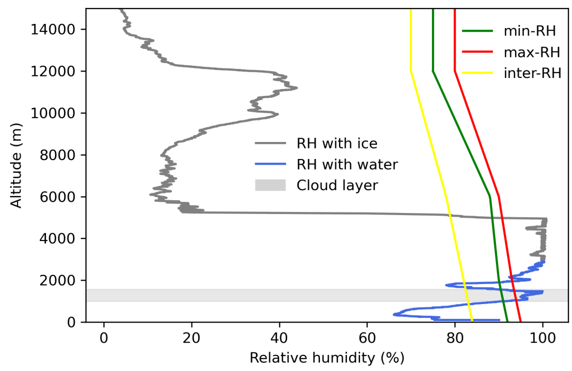


FIG. 1: Vertical profiles of relative humidity (RH) calculated with respect to water, and with respect to ice on 25/09/2022 at 00:00 UTC. The yellow, green, and red lines represent the intermediate, minimum, and maximum humidity thresholds respectively, as shown in Table I. The shaded gray area refers to the cloud layer detected.

These were the minimum and maximum relative humidity thresholds in cloud layers (min-RH and max-RH) and minimum relative humidity thresholds between two contiguous cloud layers (inter-RH)(Fig. 1). Table I sumarizes the RH thresholds for each height range used in this study.

To determine if there are clouds, it is necessary first to identify what are called moist layers. This is done in three steps:

1. The base of the moist layer is the first height where RH exceeds min-RH.
2. The top of the moist layer is the height where RH falls below min-RH, or if the layer has not closed, the top is the last height of the profile.
3. Finally, all layers where the base is below 500 m and the thickness is less than 400 m are discarded.

Once the moist layers are obtained, we proceed to determine if these layers are clouds or not by following three more steps:

1. If the maximum RH within the layer is greater than the min-RH evaluated at the base of the moist layer, this layer is considered as a cloud.
2. If the distance between two adjacent layers is less than 300 m or the minimum RH is greater than the maximum value of inter-RH evaluated at the distance separating them, the layers are merged into one and accepted as a cloud.
3. Finally, all clouds with a thickness of less than 100 m are discarted.

As it was pointed out, this methodology does not account for possible deviations of the radiosonde balloon, which could interfere with the complete detection of the cloud.

III. RESULTS

A. Days with cloud detection from 2003 to 2022

To analize the number of days with cloud detection all years with fewer than 600 radiosonde observations has not been considered. Without this quality control, having fewer radiosonde data would also result in detecting fewer clouds, thus leading to misleading results.

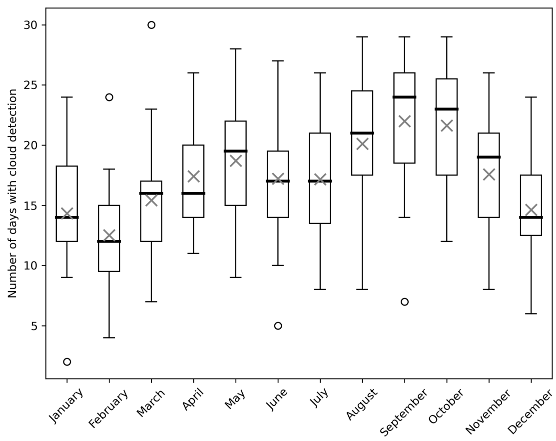
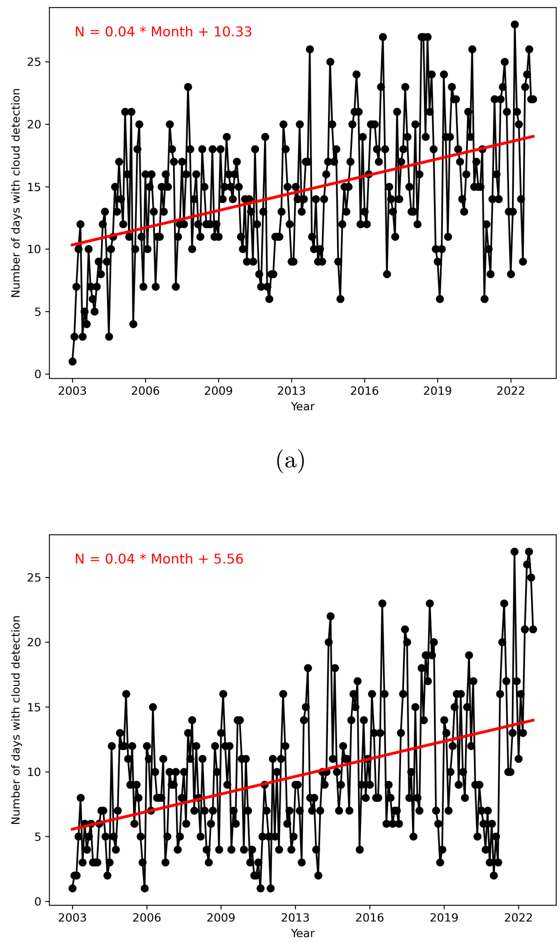


FIG. 2: Boxplot of the number of days with cloud detection by month, from year 2003 to 2022. The white boxes represent the interquartile range (IQR), containing 50% of the central data; the black line inside the box is the median; the whiskers extend up to 1.5 times the IQR from the lower and upper quartiles; the cross inside the box indicates the mobthly mean value, and the points outside the whiskers are the outliers.

Fig. 2 shows the high variability in the number of days with cloud detection throughout the year. The anual distribution shows two maxima, one in September-December (autumn) and the other one in May (spring). The average number of detections is higher than 20 per month in autun but it is around 12 in winter. May and August show the highest variability (large box and whiskers). The outliers in January and June are from year 2003, February from 2018, March from 2022, and September from 2011.

This pattern could be explained by the fact that in the summer and spring months, the air and surface temperatures increase, which in turn increases convection, potentially leading to greater cloud formation. In these months, the evaporation of bodies of water is more likely, increasing the amount of water vapor in the atmosphere. This increase in humidity could favor cloud formation.



(a)

(b)

FIG. 3: Monthly number of days with cloud detection from 2003 to 2022 for sondes launched at around 00:00 (a) and at 12:00 UTC (b). The lineal regressions are denoted with a straight line. The slope of the regressions is in units of day/month, where day refers to the number of days with cloud detection.

Fig. 3 demonstrates a notable positive trend in of the number of days with cloud detection over the years. Remarkably, both the 00:00 and 12:00 data sets show the same increase rate. Specifically, we found an increase of 0.04 days with cloud detection per month. This increasing trend could be due to a global rise in temperatures, as this way, the amount of water vapor in the atmosphere can be greater, which can lead to a greater formation of clouds. Another important factor could be air quality, as pollution, especially aerosols and suspended particles, can act as condensation nuclei, increasing cloudiness [6]. This study is conducted in Barcelona, a city characterized by high urban activity, which promotes pollutant emissions that may also contribute to increased cloudiness.

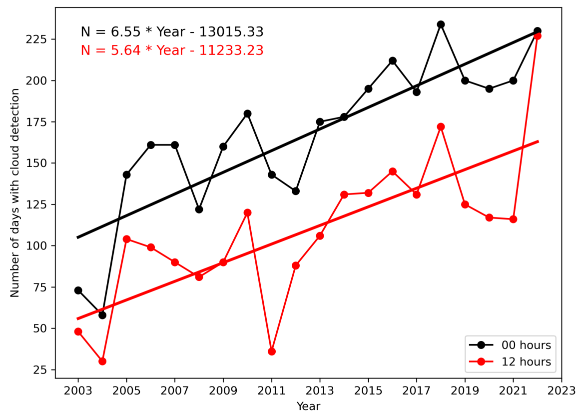


FIG. 4: Number of days with cloud detection over the year from 2003 to 2022. The lineal regressions are denoted with a straight line. The slope of the regressions is in units of day/year, where day refers to the number of days with cloud detection.

In Fig. 4 there is also a growing trend in the number of days in a year with cloud detection, which is explained by the same reasons mentioned earlier. However, now a slight difference in the growth rate of days with cloud detection is observed. A higher detection rate is noted for data filtered at 00:00 with 6.55 day/year, while for data filtered at 12:00, the value is 5.64 day/year. The fact that the black lines are above the red ones indicates that during the night (radiosonde data at 00:00) there are more days with cloud detection than during the day (radiosonde data at 12:00). This phenomenon could have a physical explanation since, during the night, in the absence of solar radiation, the atmosphere tends to be more stable, which can allow existing clouds to persist and new clouds to form [7].

It is important to note that this study does not analyze the amount of clouds in the sky, as the radiosonde only provides information of the vertical profile, not the horizontal variation. The results obtained show that there is more cloud detection, but this term should not be confused with the number of cloudy days, as detecting a cloud does not imply overcast conditions.

B. Cloud vertical structure from 1998 to 2022

As it was pointed out previously, in the study only the lowest cloud layer has been taken into account, i.e., the first cloud detected. For this section, we have indeed used all the available data from the radiosondes (from 1998 to 2022).

In Fig. 5a, a negative trend in the base height of the first clouds is observed, specifically a decrease of 0.36 m/year. With these results, we might dare to say that the clouds are getting lower as their base begins closer to the surface. Acording to the method, for clouds to have a lower base, it must be the case that near the surface, the relative humidity increases in order to surpass the min-RH threshold at a lower height. This increase in relative humidity may be strongly related to a global increase in temperature, as it was expleined

On the other hand, Fig. 5b shows a small positive trend in the top height of the first cloud, with an increase of 0.09 m/year. We highlight that in absolute terms, this trend is smaller than the observed in Fig. 5a. Similarly the reasoning described earlier, which assumes that due to rising temperatures relative humidity increases, is consistent with our method, as to determine the top of our humid layer, we took the height where relative humidity ceased to be greater than min-RH. Therefore, due to this increase in relative humidity, the top of the humid layer also rises.

The absolute maxima observed in both Fig. 5a and Fig .5b belong to August 2003, a year with a strong heatwave. Most relative maxima are located in the months of June, August, and September, which also agrees with our hypothesis that an increase in temperature may lead to an increase in relative humidity.

Fig. 5c is the result of the difference between the two previous. If, on the one hand, the base of the cloud extends downward, and on the other hand, the top extends upward, the final result will be a thicker cloud. We observe an increase in the thickness of the first cloud by a value of 0.46 m/year. In this case, specifying in which months the maxima occur is not relevant since no privileged time of the year is observed. This phenomenon, being strongly related to those explained previously, can also be explained by the same reasons.

Comparing the results with those obtained by [4], some slight differences are detected. It is important to note that they conducted the study for all clouds whereas we only studied the first one, namely the lowest. Unlike us, they found a positive value in the increase of the cloud base height. It is also noteworthy that, in absolute terms, the slope value of their regression lines is considerably higher than those found during this study. These differences are believed to be largely due to the location from where the radiosondes were launched. It is very likely that near the coasts the air is more humid, influencing relative humidity and cloud formation. In our case, the radiosondes were launched from Barcelona, Spain, a coastal city, while in [4] they were conducted in Lindenberg, Germany, which is about 200-250 km away from the nearest coast. Another differential factor could be that in our study data from 1998 to 2022 were used, whereas in [4] data from 1992 to 2020 were utilized.

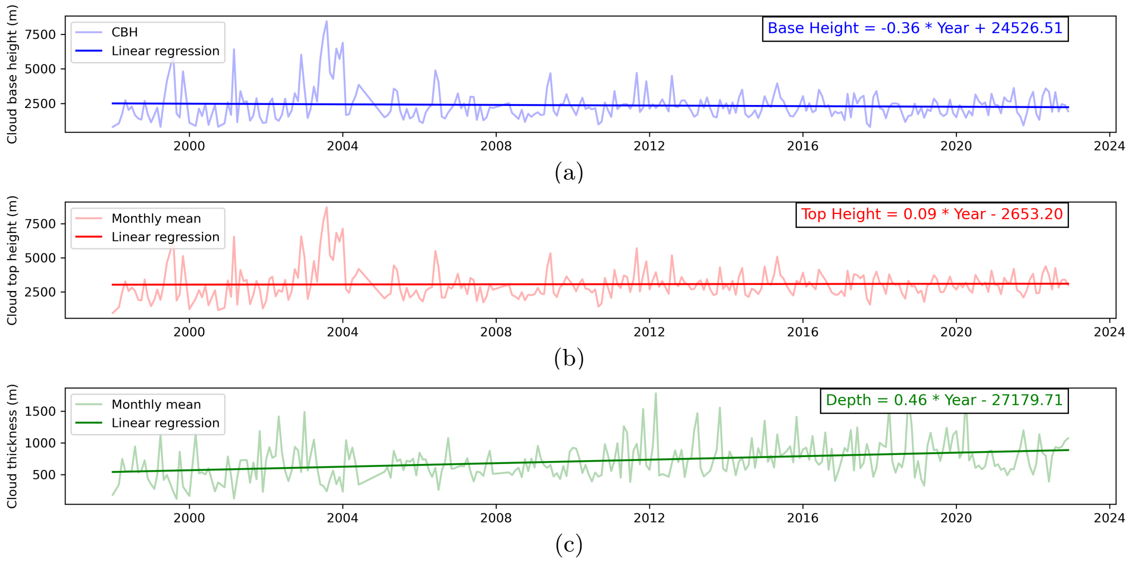


FIG. 5: Monthly mean (a) cloud base height, (b) cloud top height, (c) cloud thickness of the first cloud. The lineal regression is denoted with a straight line. The slope of the regretions is in units of m/year.

IV. CONCLUSIONS

An analysis on the long-term evolution of the CVS of the first detected clouds and the number of days with cloud detection has been conducted, based on measurements from radiosondes launched twice daily (around 00:00 and 12:00 UTC) from 1998 to 2022 for the CVS study and from 2003 to 2022 for the study of cloudy days. A significant increase in the number of days with cloud detection over the years was found. Specifically, a monthly increase of 0.04 days per month for both 00:00 and 12:00 h, an annual increase of 6.55 days per year at 00:00 hours, and an increase of 5.64 days per year at 12:00 hours were observed. Additionally, greater variability was observed during the autumn and summer months. Regarding the study of cloud base height, cloud top height, and thickness, variations of -0.36 m/year, 0.09 m/year, and 0.46 m/year, respectively, were identified.

We believe that a very important factor influencing cloud appearance and CVS variation is the global temperature increase. However, the purpose of this work is not to identify all the effects of climate change on cloud formation, as this process depends on many other factors besides those we have considered.

In the future, it could be considered to implement certain improvements in data analysis. For example, all radiosonde data that differ by a certain distance from the launch point could be removed. It could also be beneficial to establish a relationship between the data from different radiosondes models to correct any possible differences that may have been overlooked in this study. Longer time series, as well, a higher number of radiosondes per day could improve the results as this would provide more data.

V. ACKNOWLEDGMENTS

We would like to thank the Catalan Meteorological Service for the provision of the radiosonde data. I also thank my tutor Yolanda Sola for her invaluable support and my family for their constant encouragement.

[1] King, M.D., et al. ”Spatial and temporal distribution of clouds observed by MODIS onboard the Terra and Aqua satellites.” IEEE transactions on geoscience and remote sensing 51.7 (2013): 3826-3852.

[2] Lu, X, et al. ”Satellite retrieval of cloud base height and geometric thickness of low-level cloud based on CALIPSO.” Atmospheric Chemistry and Physics 21.15 (2021): 11979-12003.

[3] Ingleby, B. “An assessment of different radiosonde types 2015/2016” Vol. 807. (2017) Reading, UK: European Centre for Medium Range Weather Forecasts.

[4] Luo, H, et al. ”Robust variation trends in cloud vertical structure observed from three-decade radiosonde record at Lindenberg, Germany.” Atmospheric Research 281 (2023): 106469.

[5] FAO. Humidity Calculations. Aviable at https://www.fao.org/3/y7223e/y7223e0i.htm (last accessed 12/06/2024).

[6] Dagan, G, et al. ”Radiative forcing from aerosol–cloud interactions enhanced by large-scale circulation adjustments.” Nature Geoscience 16.12 (2023): 1092-1098.

[7] Velasteguí, A.X.H , et al. ”Evaluación de la estabilidad atmosférica bajo condiciones físicas y meteorólogicas del altiplano ecuatoriano.” Revista Brasileira de Meteorologia 33 (2018): 336-343.