# Environmental episode in Barcelona due to a Saharan dust outbreak

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**Abstract:** Between 23/02/2021 and 26/02/2021, the *Generalitat de Catalunya* declared an environmental episode in the Barcelona area due to a Saharan dust outbreak. For its depiction, $PM_{10}$ concentration measurements and ceilometer data from Palau Reial station, along with backward air mass trajectories, have been analyzed. The $PM_{10}$ concentration in Palau Reial exceeded 50 $\mu g/m^3$ for about 8 $h$ on 23/02/2021. This threshold was surpassed and sustained for several days in other stations belonging to the *Zona de Protecció Especial*, leading to the declaration of the environmental episode. These findings align with the ceilometer data, which revealed a significant aerosol presence near ground level through the planetary boundary layer. Its thickness was below 750 $m$ most of the time. Additionally, the course and height of the air masses confirm the long-range transport of air originating from Saharan regions, as well as the key role of the Atlas mountain range in lifting dust into the free troposphere in this episode.
**Keywords:** Aerosol concentration, backward trajectories calculation, ceilometer, programming.
**SDGs:** This work is related to SDGs 3, 11 and 13.

## I. INTRODUCTION

The impact of atmospheric aerosol –specifically particulate matter (PM) in the form of mineral dust– on the changing climate is conspicuous. Indeed, its effects have been proven to worsen air quality and heavily impact society and the economy. Especially during extreme events, this poses a danger to maritime and air navigation, the efficiency of solar energy and human health. Hence, the proper study and monitoring of the variability of aerosol concentration, as well as its transport and distribution on local and synoptic scale are becoming popular practice in the scientific community [1].

The major natural sources contributing to the generation of atmospheric aerosol particles are located in arid regions across North Africa, the Middle East and inner Asia. They account for up to 70% of global dust emissions [2]. Particularly, the Sahara Desert is the predominant source of airborne dust particles, amounting to half of the global generation of mineral dust.

The determination of the specific direct and indirect radiative effects of aerosol particles on climate variability has proven to be a highly complex task. Firstly, aerosol's spatial and temporal distribution is constantly changing due to sources and transport. Secondly, the characterization of the components and ratios of aerosol heterogeneous mixtures is incomplete, and thirdly, there is still little knowledge about the mechanisms related to the interactions between clouds and PM [3].

Nowadays, several observational networks aim to both minimize these uncertainties and improve the current PM characterization prospects on optical and microphysical properties. These include EARLINET, which analyses the vertical PM distribution via the implementation of both ground-based and advanced lidar systems, ACTRIS, which provides ground level information over Europe, or AERONET, which uses robotic sun and sky photometers to estimate the column-integrated aerosol properties [4].

A variety of meteorological scenarios in the synoptic scale cause the injection of North African dust into the atmosphere. Oftentimes, the dust is transported at different heights, crossing the Mediterranean sea and arriving to the Iberian Peninsula as a dust intrusion [5].

Between 23/02/2021 and 26/02/2021, the *Generalitat de Catalunya* declared an environmental episode in the area of Barcelona as a result of a Saharan dust outbreak. This work aims to characterize the dust intrusion scenario with different types of data and its corresponding analysis and interpretation. Whether the methodology followed and the results obtained are sufficient for an environmental episode depiction is also discussed.

## II. DATA AND METHODOLOGY

Before outlining the procedures followed for the data analysis, it is necessary to address the definition of an environmental episode and how it is detected from surface air quality stations. Then, trajectories are deconstructed going backward in time in order to analyze the origin of the air masses arriving in Barcelona during the episode. Finally, data from a Vaisala CL31 ceilometer is clearly represented to attempt to detect the environmental episode locally and understand the vertical evolution of particulate matter (PM) until its deposition at ground level.

### A. The environmental episode

The registered environmental episode starting on the 23/02/2021 and ending on the 26/02/2021 has been chosen for the development of this work. The selection was based on data availability and the intensity of the episode. Although environmental episodes are more frequently affecting the Iberian Peninsula, the northeast of the territory is not as influenced by this phenomenon as

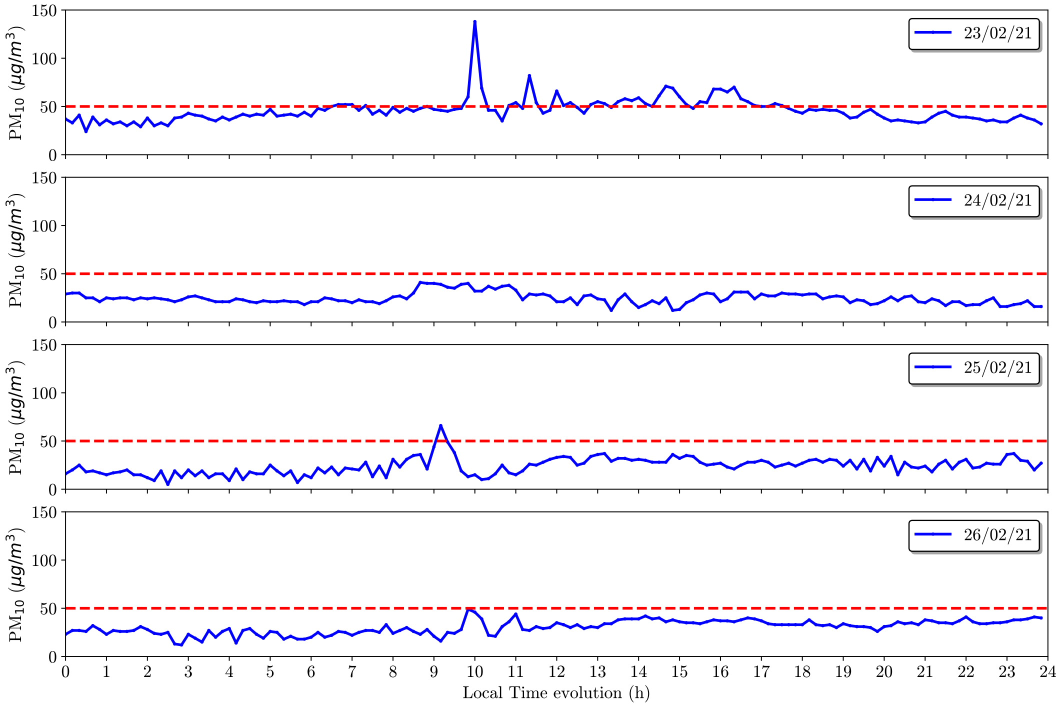


FIG. 1: Concentration of $PM_{10}$ during the environmental episode in the Palau Reial (PR) measuring station. In red, the $50\mu g/m^{-3}$ mark.

other regions, such as the south and some central areas. Thus, a strong environmental episode has a greater chance of capturing the PM effects in this study.

High daily means of PM with diameter up to 10 $\mu m$ ($PM_{10}$) concentration may cause a preventive warning and an environmental episode if certain thresholds are exceeded. The first is intended to report an increase in the concentrations above the threshold of 50 $\mu g/m^3$ in more than one station together with a forecast sustained for at least 24 $h$. When in more than one station the daily mean surpasses 80 $\mu g/m^3$ or the 50 $\mu g/m^3$ threshold is surpassed for several days, an environmental episode is declared [6].

In order to analyze $PM_{10}$ concentration levels during the environmental episode in Barcelona, data files published by the Department of Environment and Sustainability of the *Generalitat de Catalunya* have been used [6]. The files register $PM_{10}$ concentration on a surface level every 10 minutes for the stations belonging to the *Zona de Protecció Especial* (ZPE). To calculate daily means, a Python code is used. $PM_{10}$ is measured with the GRIMM EDM 180 automatic system. Using a laser based technology, it detects the amount and size of particles present in the atmosphere with a resolution of 0.1 $\mu g/m^3$.

The analysis focused on Palau Reial (PR) station, since a deeper study through ceilometer data is carried out in the same coordinates. Figure 1 displays the daily evolution of $PM_{10}$ concentration in PR station during the environmental episode. The limit value of 50 $\mu g/m^3$ is added to help visualize the exceedances of concentration over time.

### B. Backward Trajectories

Backward trajectories (BTs) have been calculated to determine the origin of the air masses arriving to Barcelona. BTs were computed with the HYSPLIT Trajectory Model using meteorological variables from the Global Forecast System (GFS) with a spatial resolution of 0.25° [7]. The specification of the starting point of the BTs is required. For Barcelona, this corresponds to latitude $41.35°N$ and longitude $2.16°E$. The elevation terrain of the BT model is also purposefully recorded, as it is later analyzed.

The data files contain 120 $h$ BTs at the starting time at two initial heights above mean sea level (AMSL). The BTs coordinates and heights, as well as the orographic terrains, are recorded with a frequency of a value per hour. The registered parameters are processed using Python to generate images that portray the route followed by the dust outbreak.

### C. Ceilometer

For aerosol characterization, lidar systems, though effective, require the presence of trained staff in order to ensure continuous functioning. Furthermore, the ele-

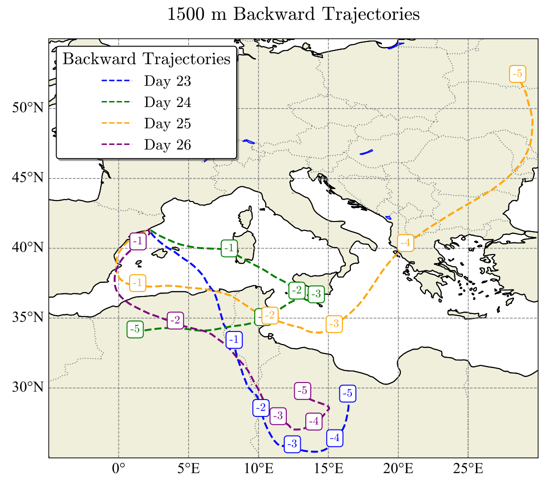


FIG. 2: BTs followed by the air masses with initial height at 1500 $m$ AMSL going back 120 $h$ from their origin at 09 : 00 $h$ UTC each episode day. The labels refer to multiples of 24 $h$.

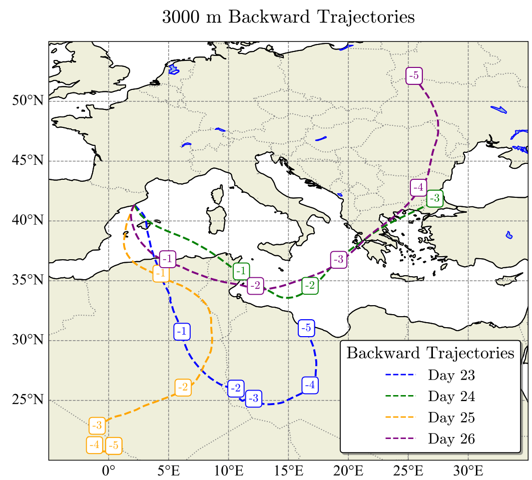


FIG. 3: BTs followed by the air masses with initial height at 3000 $m$ AMSL going back 120 $h$ from their origin at 09 : 00 $h$ UTC each episode day. The labels refer to multiples of 24 $h$. The BT corresponding to the 24th stops on the third day because the remaining route exceeded the frontiers of the map and its inclusion worsens image clarity.

vated cost of the instrument becomes a handicap for a network operating unit [3]. Ceilometers are lidar-based instruments initially designed for cloud base detection. They operate by emitting low energy pulses at a single wavelength, typically near infrared, and processing the backscattered light by atmospheric PM. Their lower cost compared to lidars and their capability to operate unattended have made this instrument a good candidate for network deployment. In addition, with recent improvements, aerosol characterization using ceilometers has been successfully tested [4].

In this study, a ceilometer Vaisala CL31 placed on the rooftop of the Physics faculty is used. The instrument provides daily data files with information recorded every 16 $s$ containing vertical profiles of atmospheric backscatter (BS) in hexadecimal notation. The Vaisala BL-View software processes these profiles and additionally provides up to three values for both cloud base height (CBH) and planetary boundary layer (PBL) height.

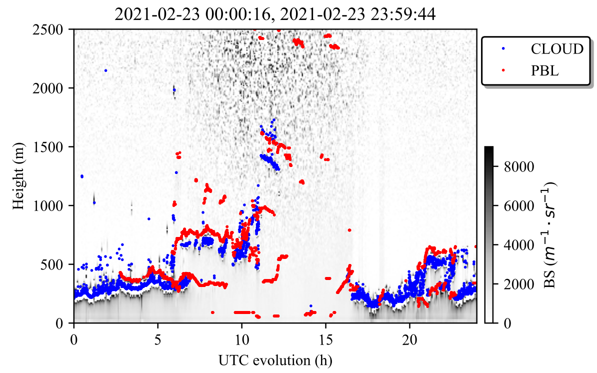


FIG. 4: BS background representation, BCH and PBL values on the 23rd.

Figure 4, obtained by processing this data using Python, shows the daily evolution of the BS signal on 23/02/2021. The ceilometer model operates with a laser wavelength of 910 $nm$, which is precise enough to detect $PM_{10}$. CBHs are added since the high scattering droplets of cloud lowers the ceilometer signal and invalidates the data above CBHs. PBL heights are also included, as they can be an indicator of surface conditions and favorable scenarios for aerosol dilution. The election of a gray intensity scale against a colored one for BS representation on Figure 4 not only neatly illustrates CBH and PBL height values, but also makes discerning different BS intensities easy.

## III. RESULTS

In this section, the previously displayed definitions, data and figures have been interpreted towards the characterization of the environmental episode that took place between the 23/02/2021 and 26/02/2021 in the area of Barcelona.

Table 1 shows the daily means of $PM_{10}$ concentration of 3 stations in the Barcelona metropolitan area and the Manlleu station, which is also included to portray the territorial extent of $PM_{10}$ increase during the episode.

The limit value of 80 $\mu g/m^3$ was exceeded by the daily $PM_{10}$ means in different stations belonging to the ZPE, as in Manlleu (Table I). Moreover, in most measuring points $PM_{10}$ mean concentration values were higher than

TABLE I: Values of the daily mean of $PM_{10}$ concentration in Palau Reial (PR), Poblenou (PN), Gràcia (GR) and Manlleu (ML).

| **Station** | **23rd** | **24th** | **25th** | **26th** |
|---|---|---|---|---|
| PR ($\mu g/m^3$) | 45.9 | 24.6 | 24.1 | 30.3 |
| PN ($\mu g/m^3$) | 52.8 | 30.3 | 36.8 | 38.3 |
| GR ($\mu g/m^3$) | 50.4 | 27.5 | 29.1 | 33.7 |
| ML ($\mu g/m^3$) | 90.3 | 56.6 | 40.9 | 42.2 |

50 $\mu g/m^3$ for a sustained period of time. Under these conditions, the environmental episode was declared.

Although in Palau Reial $PM_{10}$ daily means were also high, they were maintained below the episode thresholds, possibly due to its location, where winds and ventilation difficult particle accumulation. This is supported by the fact that PR is considered an urban background station, since it is far from industry and urban areas. Taking this into account and according to data presented in Figure 1, while the episode thresholds are not exceeded in PR, there is a high concentration of $PM_{10}$ on the 23rd. On this day, $PM_{10}$ registers oscillate between 138 $\mu g/m^3$ and 24 $\mu g/m^3$. During the remaining episode $PM_{10}$ values are generally lower and variate within 66 $\mu g/m^3$ and 5 $\mu g/m^3$.

Figures 2 and 3 illustrate the spatial and temporal evolution of BTs with initial heights of 1500 $m$ and 3000 $m$, respectively. These heights were chosen taking into consideration atmospheric transport and meteorological dynamics. They characterize the bottom and top of the free troposphere and, thus, long-range transport of the air masses. At 3000 $m$ AMSL the air mass is typically in the free troposphere, where PM transport and atmospheric processes are reflected on a synoptic scale. A 1500 $m$ height AMSL provides insights in the lower free troposphere. Moreover, dust layers originating from Saharan dust outbreaks are usually found at 1500 $m$ heights or above while being transported. Consequently, the monitoring of both initial heights serves the purpose of tracking the Saharan dust outbreak to its source. Lower heights were omitted since they tend to be influenced by turbulence and faster deposition [5].

Notably, Figures 2 and 3 reveal that the 1500 $m$ BTs corresponding to the 23rd and 26th and the 3000 $m$ BT from the 23rd all originate from the Sahara region. Figure 5 delves deeper into both BTs from the 23rd and the associated orography profiles. In both plots, initial heights are indicated. For better comparison with Figures 2 and 3, there is a vertical grid line every 24 $h$. From left to right, during the first four days of transport both air masses descend from a height of approximately 3000 $m$. This is correlated with the smaller separation between days in Saharan regions that can be observed in Figures 2 and 3, signifying a slower horizontal transport. On the 22nd, the air masses gain height while crossing the Mediterranean Sea, finally arriving to Barcelona on

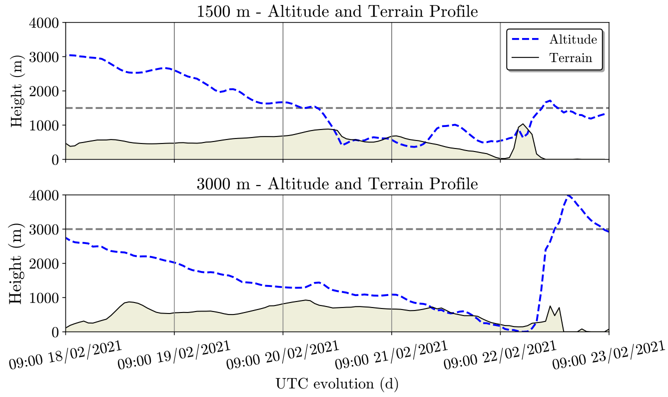


FIG. 5: BT heights AMSL of the air masses with initial height of 1500 $m$ and 3000 $m$ for the 23rd. Shaded areas represent the terrain elevation of the model below the particle position. Distances traveled each day are not represented in these figures.

the 23rd. The then larger separation between days corresponds to faster transport at higher levels. As can be seen in Figure 5, the sudden elevation of the air masses was probably motivated by the elevation of the orographic terrain under both BTs. This can be attributed to the crossing of the Atlas mountain range by both BTs just before arriving to the Mediterranean Sea (see the temporal and spatial correspondence between maps on Figures 2 and 3 and the orography changes near the 22nd on Figure 5). Moreover, low pressures on eastern Sahara regions favor the elevation of dust to layers where long distance transportation can occur.

In relation to the fact that some of the computed BTs do not originate from the Saharan region, layered transport, wind pattern variability or limitations of the HYSPLIT Trajectory Model precision are some of the factors that can bias both the course and computation of BTs [8].

As it has been discussed, the higher daily $PM_{10}$ concentration mean in the PR station is on the 23rd. In light of this, the same date is used for ceilometer data on Figure 4. High intensity values from BS can be seen near the surface, indicating the presence of aerosol particles. And, although BS values above CBHs are omitted, on the top center of Figure 4 these increase, possibly indicating a higher aerosol presence. The image shows low PBL height values, often associated with a restriction on the vertical movement of the air masses from the low free troposphere to the ground level. In this situation, most of the aerosols would still be aloft, translating into the detection of lower than expected PM concentration values [9].

## IV. CONCLUSIONS

After processing various data sources and analyzing the results, the following conclusions were drawn regarding the adequacy of the presented methodology and results in depicting the chosen environmental episode.

The overall description of the environmental episode indicates lower than expected PM concentrations in PR. This observation is supported by data from ground level air quality monitoring stations across the ZPE. Furthermore, these results align with the location of the PR station near Diagonal avenue, a clear and ventilated area distant from significant pollution sources. Another plausible explanation for a faint $PM_{10}$ detection lies in typical atmospheric behaviors associated with low PBL height values. Such conditions suggest vertical stratification of the atmosphere, which restricts vertical movement of air masses. In this scenario, dust-laden air masses situated in the low free troposphere would be unable to descend to ground level, leading to lower PM concentration registers.

BTs from the free troposphere traversed the Sahara region. A deeper height analysis revealed that the orography along these BTs likely contributed to the sudden elevation of the air masses. Furthermore, the crossing of the Atlas mountain range appears to be a critical factor in the observed rise of the air masses.

Cloud cover above the ceilometer, not only on the 23rd but throughout the entire environmental episode, limited the availability of valid ceilometer data. Although a PBL height analysis has been performed, lack of clouds would have permitted a deeper study of BS intensity profiles in order to detect aerosol descent patterns before and during the episode.

To conclude, several improvements could be implemented to enhance the characterization of the environmental episode. For instance, data collection at a less ventilated station could facilitate better detection of aerosol accumulation. Additionally, employing both a ceilometer and lidar would enable cross-validation of measurements, reducing data elimination and improving overall reliability.

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# Preparació del manuscript del TFG amb LaTeX

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**Resum:** Entre el 23/02/2021 i el 26/02/2021 la Generalitat de Catalunya va declarar un episodi ambiental a la ciutat de Barcelona causat per una intrussió de pols sahariana. Per la seva descripció, s'han analitzat mesures de la concentració de $PM_{10}$ i dades de ceilòmetre provinents de l'estació de Palau Reial, amb retrotrajectòries de masses d'aire. La concentració de $PM_{10}$ a Palau Reial va sobrepassar els 50 $\mu g/m^3$ al voltant de 8 $h$ el dia 23/02/2021. Aquest llindar va ser superat i prolongat durant dies en altres estacions dins la Zona de protecció Especial, portant a la declaració de l'episodi ambiental. Aquests resultats concorden amb les dades de ceilòmetre, que mostren una presència d'aerosols significativa prop del terra mitjançant la capa de barreja, que va presentar un gruix de menys de 750 $m$ la majoria del temps. A més, el trajecte i l'alçada de les masses d'aire confirmen el transport de llarga distància d'aire amb origen al Sàhara i el paper imprescindible en aquest episodi dels Atlas en elevar la pols fins la troposfera lliure.
**Paraules clau:** Concentració d'aerosols, càlcul de retrotrajectòries, ceilòmetre, programació.
**ODSs:** Aquest TFG està relacionat amb els ODSs 3, 11 i 13.

### Objectius de Desenvolupament Sostenible (ODSs o SDGs)

| | | | |
|---|---|---|---|
| 1. Fi de la es desigualtats | | 10. Reducció de les desigualtats | |
| 2. Fam zero | | 11. Ciutats i comunitats sostenibles | X |
| 3. Salut i benestar | X | 12. Consum i producció responsables | |
| 4. Educació de qualitat | | 13. Acció climàtica | X |
| 5. Igualtat de gènere | | 14. Vida submarina | |
| 6. Aigua neta i sanejament | | 15. Vida terrestre | |
| 7. Energia neta i sostenible | | 16. Pau, justícia i institucions sòlides | |
| 8. Treball digne i creixement econòmic | | 17. Aliança pels objectius | |
| 9. Indústria, innovació, infraestructures | | | |

El contingut d'aquest TFG, part d'un grau universitari de Física, es relaciona amb l'ODS 3, i en particular amb la fita 3.9, ja que contribueix a la reducció de morts causades pels efectes de la pol·lució de l'aire. També es pot relacionar amb l'ODS 11, fita 11.6, perquè participa en l'estudi de l'impacte ambiental dels aerosols en la qualitat de l'aire i amb l'ODS 13, fita 13.3 ja que millora la conscienciació en relació amb la mitigació del canvi climàtic.

### GRAPHICAL ABSTRACT