# Fingerprint of transported smoke from 2023 wildfires in Greece on aerosol optical properties

Author: Genís Bellvehí Mora.
*Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.*[*]

Advisor: Yolanda Sola

**Abstract:** Wildfires represent a growing global environmental challenge, and the 2023 fire season in Alexandroupolis, Greece, marked a significant event. This study analyzes columnar aerosol optical properties during this wildfire and a Saharan dust intrusion, and compares them with the 2021 Athens wildfires. Results reveal a peak in aerosol concentration in Thessaloniki during August 23, with an aerosol optical depth (AOD) at 440 nm of 2.8. The Angstrom exponent (AE) at 440-870 nm reaches values of 2.2, indicating small sized particles with higher absorption at longer wavelengths. The Saharan dust event on August 18 exhibits small AE values (0.1 to 0.5) due to coarser particles, which have higher absorption at shorter wavelengths. Changes in columnar optical aerosol parameters were similar to those of 2021 with slight differences in particle size. This study shows the influence of medium range transport of aerosols from wildfires affecting air quality.

## I. INTRODUCTION

Wildfires, characterised by uncontrolled and rampant combustion of vegetation, have emerged as a global environmental challenge, leaving a permanent mark on ecosystems and human societies. In recent years, there has been a surge in the frequency and intensity of wildfires, connected with climate change and other factors, such as land-use change and arson fires. The consequences of wildfires are varied, including ecological disruption, loss of biodiversity, damage to infrastructures, and notably, the release of large quantities of aerosols into the atmosphere. The effects extend far beyond the immediate regions of ignition, in particular due to meteorological conditions.

In 2022, the European Union experienced its second-worst wildfire season since 2000, when records began for Copernicus' European Forest Fire Information System (EFFIS), surpassed only by the 2017 fire season. EFFIS detected 16,941 fires in 45 countries in 2022 burning 1,624,381 ha [1]. Greece has been one of the regions most affected by wildfires in recent years. A total of 94,000 ha burned in 2021 spread over five large fires. In August, almost 70,000 ha were recorded in three locations around Athens [2]. In 2023, the affected area amounted to 174,000 ha. In particular, the wildfire in Alexandroupolis Municipality is considered the largest fire recorded in the European Union since 2000, with a burnt area of 82,559 ha, according to EFFIS.

Atmospheric aerosol, comprising solid or liquid particles suspended in the atmosphere and varying in size from hundreds to thousands of microns, modify the Earth's energy balance. Additionally, they affect air quality and have consequences for human health. Those particles that are injected into the atmosphere directly are known as primary aerosols, for example, sea spray, mineral dust, smoke and volcanic ash. Secondary aerosols are formed when substances (e.g., gases) undergo chemical reactions in the atmosphere, transforming into aerosol particles after their initial emission in a different form, such as sulfate aerosols from volcanoes or industrial emissions [3]. In this study, we focus on aerosol emitted from wildfires.

In current research, remote sensing networks have become essential tools for monitoring and characterising aerosols. There are two main categories: terrestrial remote sensing, which uses instruments (e.g., radars and photometers) placed on the Earth's surface, providing high spatial resolution and detailed observations of specific areas; and satellite-based remote sensing, which uses instruments in orbit, enabling global monitoring but with a potential reduction in spatial resolution. We target on terrestrial remote sensing, specifically analyzing data from Aerosol Robotic Network (AERONET [4]).

The objectives of this work are (1) to analyze the columnar aerosol optical properties at several stations affected by the wildfire that took place in Alexandroupolis in August 2023, (2) to show and identify the differences between these parameters during the wildfire episode and in a Saharan dust intrusion, and (3) to compare them with those of the Athens wildfires in August 2021.

## II. DATA AND METHODOLOGY

AERONET is a ground-based network for measuring optical and physical properties of atmospheric aerosol, with more than four hundred stations distributed globally. This network operates with a CIMEL CE318 sun/sky photometer, which measures direct solar radiation (DSR) and sky radiation at different wavelengths. DSR varies with to the presence of aerosols, water vapor, Rayleigh scattering and certain gases in the atmospheric column. The attenuation of the DSR reaching the photometer is linked to the concept of total opti-

[*]Electronic address: genisbellvehi@gmail.com

cal depth ($\tau_{TOT}$), obtained according to Beer-Lambert-Bouguer law:

$$V(\lambda) = V_0(\lambda)\ d^2\ exp[-\tau_{TOT}(\lambda) \cdot m] \quad (1)$$

where V and $V_0$ are the digital voltage, which is proportional to the spectral irradiance reaching the instrument at the surface, and the extraterrestrial voltage, respectively. $V_0$ is proportional to the estimated top of the atmosphere spectral irradiance and is used to calibrate the instrument. These voltages are measured by the photometer at selected wavelengths $\lambda$. In addition, d is the ratio of the average to the actual Earth-Sun distance, and m is the optical air mass, which depends on the solar zenith angle [5].

Aerosol optical depth (AOD) is the measure of the extinction caused by aerosols (e.g., smoke particles, desert dust) distributed within a column of air from the photometer to the top of the atmosphere. AERONET provides this value as a direct sun product, taking into account the optical depth of the other atmospheric components mentioned: $AOD(\lambda) = \tau_{Aerosol}(\lambda) = \tau_{TOT}(\lambda) - \tau_{water}(\lambda) - \tau_{Rayleigh}(\lambda) - \tau_{gases}(\lambda)$, where gases comprise $NO_2$, $CO_2$, $O_3$, $CH_4$ and others.

Another direct sun product that we analyze is the Angstrom exponent (AE), calculated as the negative slope (or first derivative) of AOD with wavelength in logarithmic scale:

$$\alpha = -\frac{dln\tau_{Aerosol}}{dln\lambda} \quad (2)$$

Values of $\alpha$ close to 2 suggest the prevalence of fine mode particles (e.g., smoke), while values near zero indicate the presence of coarse mode particles, such as desert dust.

From sky radiation measurements and applying inversion methods, AERONET estimates other optical parameters of aerosols. Specifically, we analyze the volume size distribution (VSD), which refers to the distribution of particle volumes within a given range of particle sizes, and the single scattering albedo (SSA), which is the ratio of the scattering efficiency to the total extinction efficiency. For these parameters, we have selected a specific hour for each station on the days studied (August 18 and 23).

AERONET products are computed for three data quality levels: Level 1.0 (raw), Level 1.5 (cloud screened), and Level 2.0 (post-calibrated and quality assured). In this study, only Level 1.5 data are considered, as the data are calibrated once a year.

To analyze the source and transport of aerosols emitted from wildfires, we employ the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model [2], which uses a hybrid of Lagrangian and Eulerian approach to compute the trajectory of a particle at different heights from meteorological fields. In this analysis, we determine 72h backward/forward trajectories at 500 m, 1500 m and 3000 m using stations as starting/ending points from Global Forecast System (GFS) meteorological datasets (horizontal resolution 0.25°). These three heights above ground level are related to different atmospheric layers characterised according to meteorological conditions, wind and friction. The 500 m height level is within the mixed layer that typically can reach up to about 1500 m, and the 3000 m level is associated with the free atmosphere, where the surface has almost no influence.

To make a selection of monitoring stations, we first apply filters to AERONET, requesting active stations with data during August 2023. In total, we review 20 stations located in Greece and its surroundings, reaching, for example, stations in Măgurele (Romania) or Medenine (Tunisia), located at $\sim$ 735 km in the southwest and at $\sim$ 1300 km northeast of Greece, respectively. To focus this analysis, we narrow down this initial dataset by examining the synoptic situation in the region during the wildfire days, using the back trajectories provided by HYSPLIT. After this search, we specify the number of stations to a total of 7, located between Greece and Italy. The location of each station is detailed in Table I.

| Station | Location (°) | Height (m a.s.l.) |
|---|---|---|
| Thessaloniki | 40.6N, 23.0E | 60.0 |
| Athens | 38.0N, 23.8E | 215.0 |
| Napoli | 40.8N, 14.3E | 50.0 |
| Messina | 38.2N, 15.6E | 15.0 |
| Potenza | 40.6N, 15.7E | 820.0 |
| Lecce | 40.3N, 18.1E | 30.0 |
| Lampedusa | 35.5N, 12.6E | 45.0 |

TABLE I: Overview of the stations, including their respective locations in degrees and heights expressed in meters above sea level.

For this work, Python codes have been expressly created to read the AERONET data files and extract the optical parameters of interest. Different Python libraries have been employed, such as Pandas and CSV, as well as Matplotlib for the grafical representations.

## III. RESULTS AND DISCUSSION

A series of wildfires that severely affected Greece started in August 19. In this study we specifically analyze the most significant one, located in Alexandroupolis Municipality, in northeastern Greece, near the coast of the Aegean Sea and at 40 km from the Turkish border. It caused extensive damage and affected surrounding areas. The general analysis of the data from the selected stations gives an overview of the aerosol characteristics during the last days of August. The peak in aerosol optical parameters occurs between August 22 and 23, making it the focus of our study. Additionally, to complement and contrast the data from the wildfire, it is also of interest to analyze the previous days in order to compare these optical parameters. This leads us to study August 18, when a Saharan dust intrusion took place.

To analyze the synoptic situation that affected the region during the wildfire and how the transport was during this specific period of time, we focus on the trajectories shown in Fig. 1.

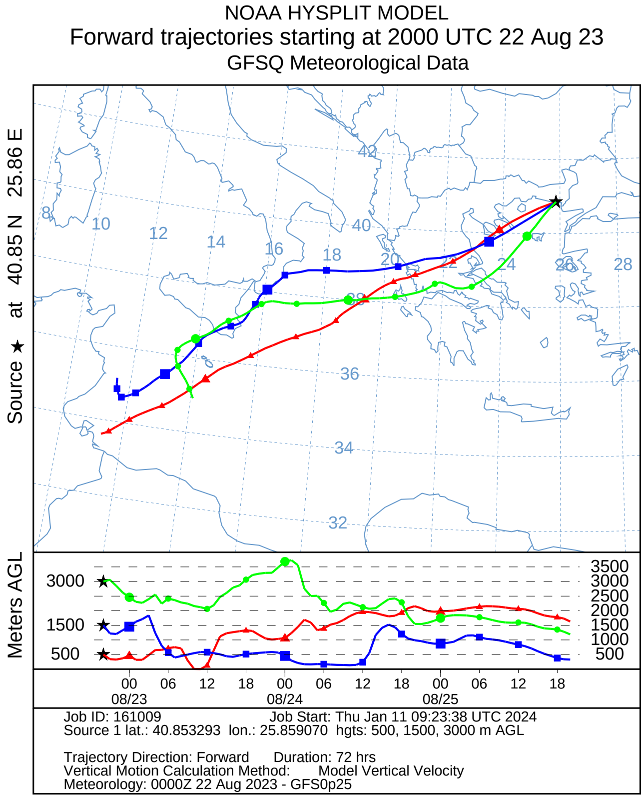


FIG. 1: 72h forward trajectories starting in Alexandroupolis at 20:00 UTC in August 22, 2023. Trajectories correspond to three heights above ground level from GFS meteorological datasets: 500 m, 1500 m and 3000 m. Figure from HYSPLIT web model output.

The forward trajectories starting on August 22 from Alexandroupolis (Fig. 1) show an air parcel transport moving to the southwest at three height levels. Furthermore, this transport direction remains similar for a period of 2 to 3 days, as observed from other HYSPLIT trajectories (not shown).

To enhance the comparison of characteristics between the wildfire period and the Saharan dust intrusion period, we analyze backward trajectories with ending point at three stations on August 18. HYSPLIT backward trajectories confirm that the origin of air masses was the Saharan desert (Fig. 2). This aerosol transport occurs at elevated height above ground level, reaching the affected stations at 3000 m, and is therefore detected by the photometers since analyze the whole vertical column. The stations affected by this Saharan dust outbreak are Messina and Lampedusa, located in southeast of Italy, while Thessaloniki is affected by particles in the mixed layer coming from the northwest. However, the presence of dust particles in other levels or accumulated from previous days is not excluded.

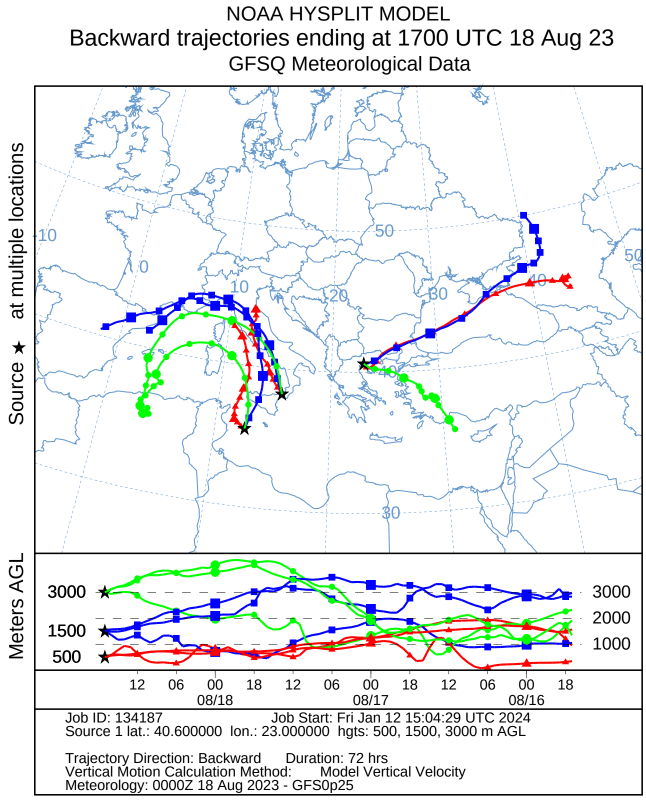


FIG. 2: 72h backward trajectories ending in Lampedusa, Messina and Thessaloniki at 17:00 UTC in August 18, 2023. Trajectories correspond to three heights above ground level from GFS meteorological datasets: 500 m, 1500 m and 3000 m. Figure from HYSPLIT web model output.

Fig. 3a shows the variation in AOD at 440 nm for several AERONET stations. There is a particular change between August 22 and 25, revealing a general increase in AOD values, especially on August 23. The Thessaloniki station exhibits a remarkable peak, reaching a maximum value of 2.8 on this particular day. This AOD peak is of particular relevance, as it indicates a very high aerosol concentration. However, since the photometer only measures during daylight hours, it is not possible to determine whether higher values were recorded at night. The overall increase in these stations suggests a broader spatial distribution of aerosol particles in the region. During the 2021 wildfires episode in Athens, peak value in AOD at 440 nm was around 2.5, slightly lower than in 2023 [2]. As for the other stations, we observe that the AOD values between August 22 and 25 are lower compared to those of Thessaloniki, despite also being affected by the fire. The reason is that these stations are located further away from the fire, resulting in a lower aerosol concentration. Regarding August 18, the AOD maintains values slightly below 0.5. Despite being aware of the Saharan dust intrusion during these days, AOD does not provide

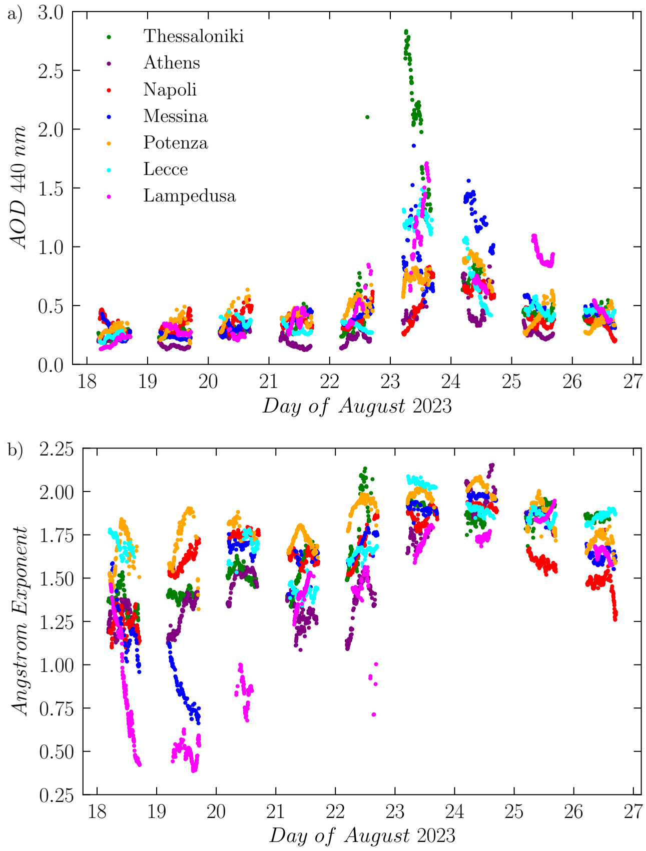


FIG. 3: Variation in a) aerosol optical depth at 440 nm and b) Angstrom exponent at 440-870 nm for different stations between August 18 and 26, 2023.

any details to distinguish this outbreak.

Fig. 3b presents the variation in the AE at 440-870 nm for various AERONET stations. We observe an increase in AE values between August 22 and 25, ranging from 2.0 to 2.2. These values indicate the presence of fine mode particles, confirming the existence of smoke in this region. In contrast to what was observed for aerosol concentration, the range of AE values is similar for all stations during this period, so all of them are directly affected by the fire. Another relevant event occurs in August 18 and 19, where AE values are close to 0 in Lampedusa and Messina, verifying the presence of coarse mode particles, related to a Saharan dust intrusion. On specific days studied during wildfires in 2021, AE values were around 2.5, a bit higher than in 2023 [2].

After analyzing AOD and AE parameters, we further reduce the number of stations, before studying inversion products parameters, to examine more clearly and conveniently the differences between wildfire and Saharan dust intrusion episodes. We focus on those stations where more extreme values stand out in either of the two episodes. These are Thessaloniki, Messina and Lampedusa.

Fig. 4 shows the variation in VSD for three different

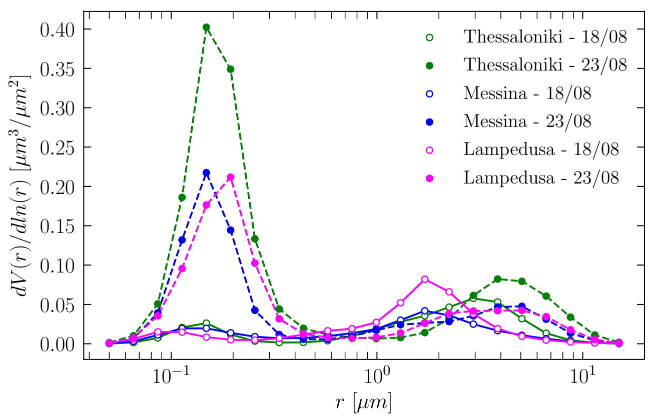


FIG. 4: Variation in volume particle size distribution for three different stations on August 18 and 23, 2023.

stations. On August 23, the VSD is dominated by small sized particles (accumulation mode), specially in Thessaloniki, reaching 0.4 $\mu m^3/\mu m^2$. The VSD values of the other two stations are close to 0.2 $\mu m^3/\mu m^2$. Regarding the 2021 Athens wildfire, this value was lower than 0.2 $\mu m^3/\mu m^2$, therefore, less than half compared to Thessaloniki and similar to Messina and Lampedusa in 2023 [2]. As for August 18, it is remarkable to highlight the VSD value for larger sized particles in Lampedusa, which is the station most affected by the Saharan dust instrusion. In Messina, this value is slightly lower, as the day with the highest incidence of the Saharan dust intrusion is day 19 (Fig. 3b).

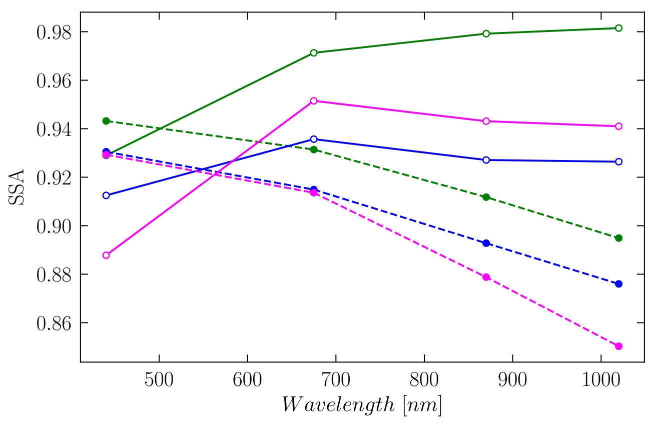


FIG. 5: Spectral variation in single-scattering albedo for three different stations on August 18 and 23, 2023. The legend is the same as Fig. 4.

Fig. 5 presents the spectral variation in SSA for three different stations. The spectral dependence of the radiative properties of desert mineral dust and biomass burning aerosol is inverse: while desert mineral dust exhibits higher absorption at shorter wavelengths due to the presence of iron oxides in its aggregates, biomass burning enhances its absorptive characteristics at longer wavelengths, resulting from the presence of elemental carbon [6]. On August 23, a strong absorption characteristic and spectral dependence is observed as the SSA decreases with wavelength from 440 nm to 1020 nm, confirming the presence of biomass burning aerosols. It decreases from 0.93 to 0.85 in Lampedusa, from 0.93 to 0.88 in Messina and from 0.94 to 0.90 in Thessaloniki. In 2021 Athens wildfires, this value decreased from 0.93 to 0.86 [2]. The SSA on August 18 increases with wavelength from 0.89 in Lampedusa and 0.93 in Thessaloniki at 440 nm to 0.94 and 0.98 at 1020 nm, respectively. This increase signifies large forward scattering due to the presence of desert mineral dust particles. The values shown for the fires, both in Alexandroupolis and in Athens, may have different aerosol composition. In addition to biomass burning, it should be considered a mixture with local aerosol [6].

## IV. CONCLUSIONS

This study has analyzed the devastating fires that affected Alexandroupolis (Greece) in August 2023 with thousands hectares of forest area burned, inducing changes in the columnar aerosol optical parameters.

- On August 23, AOD at 440 nm values reached a maximum of 2.8 in Thessaloniki and a general increase in the rest of the stations, with values above 1.0 in some of them (Messina, Lecce and Lampedusa). AE values were also high, ranging from 1.7 and 2.2 in all stations, indicating the presence of fine mode particles from the wildfire. The VSD was dominated by small sized particle reaching 0.4 $\mu m^3/\mu m^2$ in Thessaloniki and 0.2 $\mu m^3/\mu m^2$ in Messina and Lampedusa, confirming the presence of smoke. Finally, SSA showed a negative spectral dependence with increasing wavelength (from 440 to 1020 nm) due to the presence of elemental carbon in biomass burning aerosol. SSA decreased from 0.94 to 0.90 in Thessaloniki, from 0.93 to 0.85 in Lampedusa and from 0.93 to 0.88 in Messina.
- Another event that took place during August 2023 was a Saharan dust intrusion, which also modified columnar aerosol optical parameters. AOD values at 440 nm were moderated, ranging between 0.1 and 0.5, significantly lower than those during the wildfire. The main difference compared to wildfires was evident in the AE values, which declined to 0.3 during August 18 and 19, verifying the presence of coarse mode particles. The VSD on that day (August 18) was dominated by large sized particles, confirming the Saharan dust outbreak, especially for Lampedusa, where VSD reached 0.1 $\mu m^3/\mu m^2$. SSA presented a positive spectral dependence with increasing wavelength due to the presence of iron oxides in desert mineral dust aggregates. The SSA increased from 0.89 to 0.94 in Lampedusa and from 0.93 to 0.98 in Thessaloniki.
- To show the magnitude and significance of the 2023 fires, we compared them with columnar aerosol optical parameters observed from various sources during August 2021 Athens wildfires. In 2021, AOD peak at 440 nm was 2.5, slightly lower than the peak in 2023, implying a lower concentration of columnar aerosols. AE values were around 2.5, a bit higher than in 2023, indicating the presence of finer particles. The VSD value was lower than 0.2 $\mu m^3/\mu m^2$, less than half compared to Thessaloniki and similar to Messina and Lampedusa. Finally, SSA decreased with wavelength from 0.93 to 0.86, indicating similar absorption characteristics to 2023 episode.

As this study shows, wildfires, which are becoming more frequent due to climate change, have an impact on the properties of aerosols at short and medium distances from the ignition zone. This has direct implications for air quality.

**Acknowledgments**

I would like to thank my advisor, Yolanda Sola, for all the guidance during this work. I would like to acknowledge NASA and AERONET for the provision of data.

[1] EU Science Hub: `https://joint-research-centre.ec.europa.eu/index_en`, last access: 14 January 2024

[2] Masoom, A., et al. (2023): Investigation of the effects of the Greek extreme wildfires of August 2021 on air quality and spectral solar irradiance. Atmospheric Chemistry and Physics, 23, 8487–8514, `https://doi.org/10.5194/acp-23-8487-2023`

[3] NASA Earth Sciences: `https://earth.gsfc.nasa.gov/climate/data/deep-blue`, last access: 14 January 2024

[4] Holben, B.N., et al. (1998): Aeronet—A Federated Instrument Network and Data Archive for Aerosol Characterization. Remote Sensing of Environment, 66, 1-16, `https://doi.org/10.1016/S0034-4257(98)00031-5`

[5] AERONET (Aerosol Robotic Network): `https://aeronet.gsfc.nasa.gov/new_web/Documents/Aerosol_Optical_Depth.pdf`, last access: 14 January 2024

[6] García, O.E. (2008): Estudio de las propiedades radiativas de los aerosoles atmosféricos mediante técnicas de teledetección. Forzamiento radiativo, PhD Thesis, Universidad de La Laguna