ATMD-2026-306

Interactive comment on “Impact of Spectral Aerosol Radiative Forcing at the Izaña Observatory during the August 2023 Extreme Wildfires” by Rosa D. García et al.

Referee #1

Reviewer recommendation: Accept with minor revisions

General comment:

The study by Garcia et al. captures a rare near-source wildfire event at a well-instrumented high-altitude observatory, providing valuable spectral radiative forcing data that is scarce in the literature. Due to the wide range of columnar, vertical, is situ aerosol and trace gas instrument at the Izaña Observatory (IZO) it is a comprehensive multi-instrument approach with rigorous methodology and significant results.

Specific comments

Missing aerosol absorption properties: The authors note (line 122) that AERONET inversion products (SSA, asymmetry parameter) were unavailable. This is a significant limitation since: SSA is crucial for distinguishing scattering vs. absorption effects. Without SSA, the conclusion that "scattering processes" dominate relies primarily on the positive diffuse forcing rather than direct measurement. Recommendation: Discuss this limitation more explicitly and consider whether MAAP absorption data could partially compensate.

Authors: The authors thank the referee for this comment. In order to provide useful information for the discussion on the predominance of the scattering capacity of the aerosols studied from spectral observations during the events selected in this work, the time series of the Single Scattering Albedo (SSA) at 637 nm has been included. This parameter was derived from data obtained with two surface instruments already described in this study: the Integrating Nephelometer and the MAAP. This information has been added to the final manuscript, as follows:

Lines 161-168:

> ***“The Single Scattering Albedo (SSA; ω0) was calculated following Valenzuela et al. (2015), by combining the total scattering coefficient (σscat (λ)) from the nephelometer and the absorption coefficient (σ_{abs} (λ)) derived from the MAAP measurements. The absorption coefficient was obtained by multiplying the eBC mass concentration by the mass absorption cross-section of 6.6 m2 g−1, with a correction factor of 1.05 applied to account for the shift in the MAAP light source wavelength (Mülleret al., 2011). SSA was then computed at 637 nm using:***
>
> $$\omega_0(\lambda) = \frac{\sigma_{scat}(\lambda)}{\sigma_{scat}(\lambda) + \sigma_{abs}(\lambda)}$$
>
> ***where $\sigma_{scat}(\lambda)$ was interpolated to 637 nm from the nephelometer measurements using the SAE, in order to match the MAAP absorption wavelength.”***

Lines 332-334:

"…This enhanced scattering capacity is consistent with the high SSA values obtained from the surface measurements (Fig. 5 in Sect. 4.1)…"

Besides, this information has been added as an additional time series in Fig. 5(c)

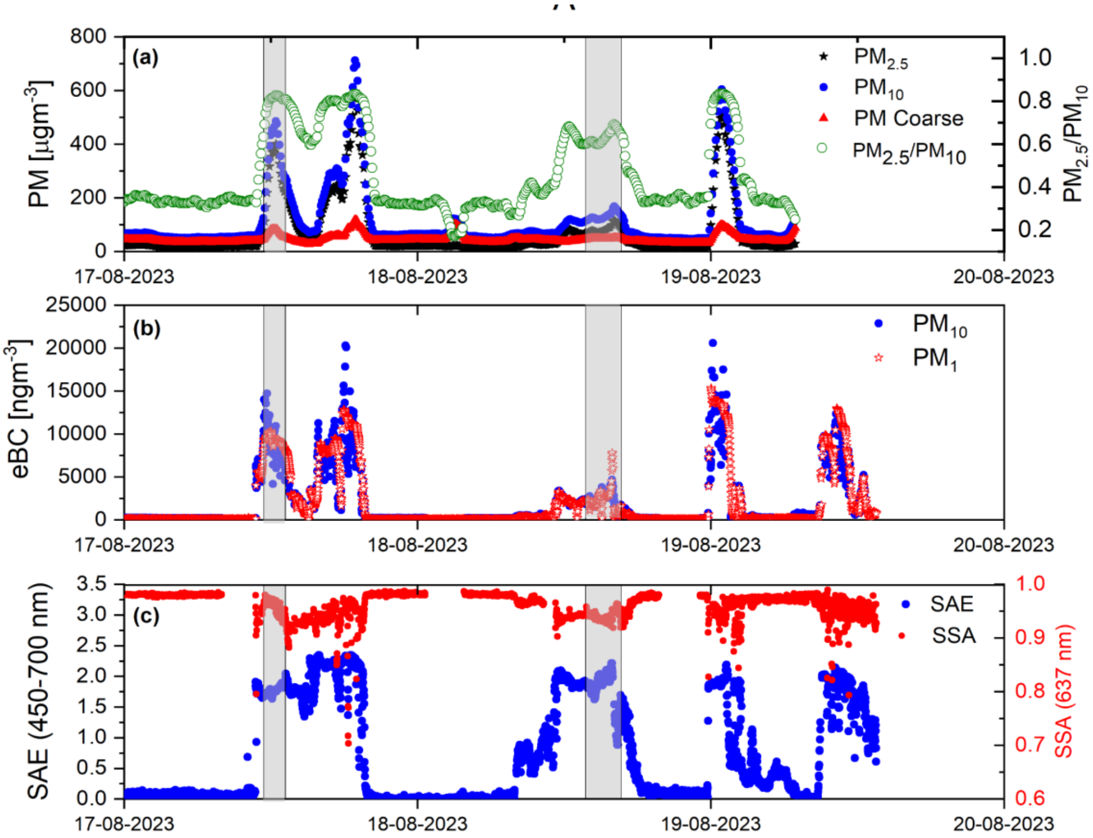


Figure 5.- *Time series of in situ aerosol measurements at IZO from 17 to 20 August 2023. (a) Mass concentrations of PM10 (black stars), PM2.5 (blue circles), coarse-mode PM (red triangles) and PM2.5/PM10 ratio (green dots, right axis). (b) Equivalent Black Carbon (eBC) concentrations for PM10 (blue circles) and PM1 (red stars) (c) SAE (450–700 nm; blue circles) and SSA (at 637 nm; red circles, right axis). Shaded areas indicate the periods corresponding to the maximum AOD values observed on 17 and 18 August.*

Limited temporal coverage: Analysis mostly focuses on two specific times (11:56 and 15:46 UTC). While understandable for detailed spectral analysis, a diurnal evolution of radiative forcing would strengthen the analysis. Recommendation: Consider adding a figure showing temporal evolution of integrated radiative forcing throughout the two days.
The comparison between 17 and 18 August would probably benefit from an analysis of measurement variability during each event.

Authors: Following the reviewer's recommendations, we have added the temporal evolution of the integrated radiative forcing throughout 17 and 18 August in Section 4.2 of the final manuscript.

Lines 367-373:

> ***“In addition to the instantaneous spectral and band-integrated forcing values discussed above, the temporal evolution of the broadband shortwave radiative forcing was analysed over the two smoke-affected days in order to evaluate the diurnal behaviour of the aerosol perturbation (Figure 9). The time series shows a clear enhancement in the magnitude of the forcing during periods of strongest smoke influence, with the largest cooling occurring around local noon, when solar irradiance is at its maximum. On 17 August, the forcing exhibits a pronounced peak between approximately 11:30 and 13:30 UTC, coinciding with the period of highest aerosol loading observed at the station. On 18 August, the forcing remains significant over a broader time interval, with a maximum around 15:30 UTC, consistent with the later arrival of the densest smoke plume (Figure 4a).”***

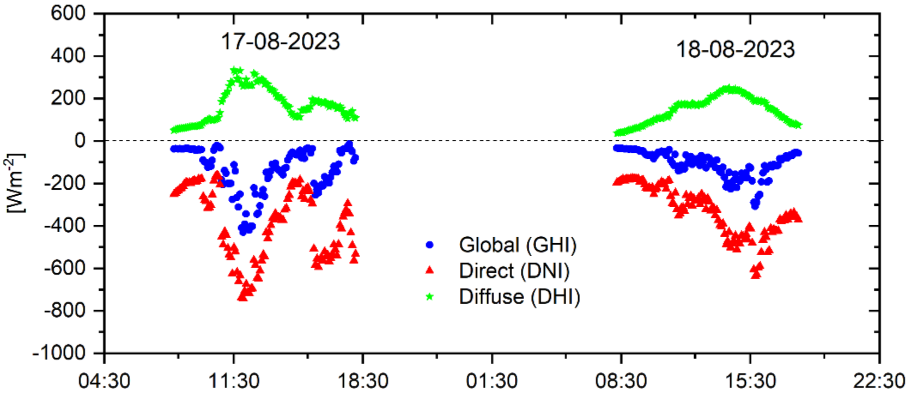


Figure 9.- *Temporal evolution of the radiative forcing components (blue: global (GHI), red: direct (DNI) and green: diffuse (DHI) radiation) at Izaña Observatory during the wildfire smoke events of 17 and 18 August 2023.*

<u>Minor comments</u>:

1. **Date/Time format**: format of date/time varies between figures (e.g. Fig. 3 and 4), consider aligning the format

<u>Authors:</u> Following the reviewer’s recommendations, we have standardized all the figures using the same date/time format in the final manuscript.

2. **Add one or two more wildfire studies** and the values mentioned therein?

<u>Authors:</u> Yes, we have included several studies on wildfires that show results consistent with ours results:

Lines 241-244:

> *“...Figure 4c confirms this dominance, with data points from 17 and 18 August clustering in the region of high AE (> 1.5) and high FMF (> 0.8) (Figure 4c), indicative of fine-mode aerosols from biomass burning (Eck et al., 2001; O’Neill et al., 2023).* ***These values are similar to those reported by Masoom et al. (2023); Michailidis et al. (2024) for the extreme wildfires that occurred in Greece in August 2021 and 2023, respectively, as well as to those reported by Filonchyk and Peterson (2024) at the El Arenosillo site in southern Europe as a result of the 2023 Canadian forest fires.”***

3. **Line 100**: "at the 4th position the shadow band stops at +5° **after** the solar disk" - Should this be "beyond" rather than "after"?

Authors: Corrected

4. **Line 222 and 232** – **reference to Masoom seems** somewhat repetitive, maybe add FMF value of Masoom to increase information value of second mention.

Authors: Following the reviewer's recommendations, we have added the FMF values reported in Masoom et al. (2023) in the final manuscript as follows:

Line 232:

> *"Simultaneously, AE > 2 on both days (2.06 on 17 August and 2.04 on 18 August) (see Table 1), indicating a predominance of fine-mode particles. These features are characteristic of biomass-burning aerosol intrusions and are comparable to those reported by Masoom et al. (2023) during the extreme wildfire episode in Greece in August 2021, where AOD values up to 3.6 at 500 nm, AE up to 2.4 (440–870 nm), **and fine-mode fraction (FMF) values around 0.98 were observed.** Therefore, the following study focuses on the events recorded on 17 and 18 August."*

5. **Table 1 and lines 259/260**: The PM2.5/PM10 ratio shows 0.81 for 17/08 and 0.66 for 18/08, but text (line 260) states "0.83 and 0.69", why is that?

Authors: The data in Table 1 correspond to the two events analysed in this study, during which the maximum AOD values were observed (grey-shaded areas in Fig. 4), whereas the values reported in the text (lines 255–260) correspond to the maximum in situ measurements (grey-shaded areas in Fig. 5). In any case, the paragraph has been updated as follows:

Lines 265-274:

> *"...The peaks on 17 August morning and 18 August afternoon (**shaded areas in Figure 5**) coincided with fire events identified from columnar properties (Figure 4). The elevated PM10 and PM2.5 concentrations within these periods indicate direct impacts from wildfire smoke plumes at the observatory, reaching maximum values of 485.19 and 167.80 µg m^{-3} for PM_{10} and 401.53 and 116.26 µg m^{-3} for PM2.5 (17 and 18 August). The eBC concentrations reached record values for the station (González et al., 2025) with **peaks** of 14.74 and 10.31 µg m^{-3} for the PM10 and PM1 size cuts on 17 August, and 4.69 and 7.81 µg m^{-3} on 18 August. Correspondingly, **the SAE, PM2.5/PM10 ratio, and SSA, which provide complementary information on aerosol size and optical properties, reached maximum values of 1.93, 0.83, and 0.98 on 17 August, and 2.21, 0.69, and 0.96 on 18 August, respectively. These values collectively confirm the dominance of fine, light-scattering wildfire originated particles during the selected events.**"*

6. **Reference list**: several times doi link wrong format: "https://doi.org/https://doi.org.." (remove one https://doi.org)

Authors: Corrected

Overall Assessment:

This is a valuable contribution documenting an extreme biomass burning event with rare spectral detail. The main scientific conclusions are sound, but the paper would benefit from a clearer discussion of limitations, particularly regarding missing SSA data. The multi-instrument approach is a major strength that validates the findings across independent measurement techniques. With the revisions outlined above the manuscript should be suitable for publication.

Authors: We acknowledge the referee's comments.

ATMD-2026-306

Interactive comment on “Impact of Spectral Aerosol Radiative Forcing at the Izaña Observatory during the August 2023 Extreme Wildfires” by García et al.

Referee #2

The manuscript “Impact of Spectral Aerosol Radiative Forcing at the Izaña Observatory during the August 2023 Extreme Wildfires” is clearly within the scope of the AMT/ACP inter-journal Special Issue “Sun-photometric measurements of aerosols: harmonization, comparisons, synergies, effects, and applications”. The study makes extensive and appropriate use of sun-photometric observations (AERONET), complemented by high-quality spectral irradiance measurements and multi-instrumental aerosol and trace-gas observations. The scientific objective is well defined and addresses a timely and relevant topic: the spectral radiative effects of extreme biomass-burning aerosols under near-source conditions. The dataset is unique, the methodology is sound, and the analysis is thorough. The use of spectral irradiance measurements combined with radiative transfer simulations to quantify spectral radiative forcing and efficiency represents a valuable contribution to the existing literature, particularly given the scarcity of such detailed spectral studies. The structure is clear, the instrumentation and methods are well described, and the results are supported by comprehensive observational evidence. Studies of this kind are valuable as we are trying to demystify the radiative effect of wildfires on climate processes, and it is very rare to be able to have such extensive data of different types and instruments so close to the source of emissions.

Authors: We acknowledge the referee’s comments.

I suggest to accept the manuscript for publication after the following minor revisions:

1. Meteorological and Plume Characterization

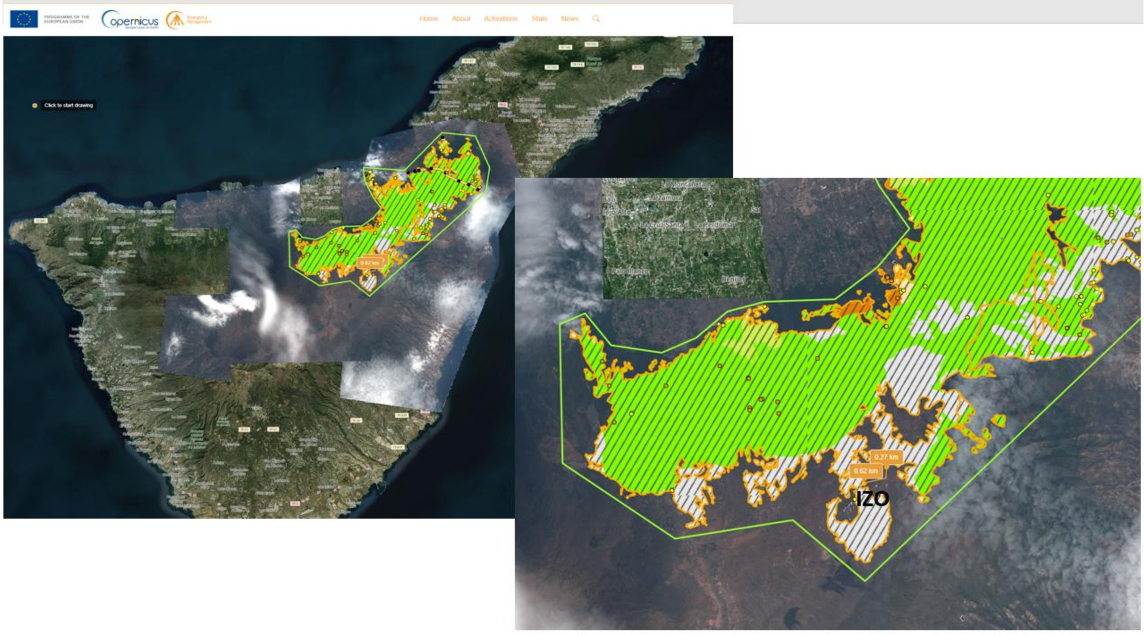
While Figure 1 provides a visual overview, more quantitative detail is needed regarding the meteorological conditions and the spatial relationship between the fire and the instruments.

Meteorological Context: Please provide more specific synoptic or local meteorological data during the wildfire peaks. While the text mentions a heatwave and low humidity, a brief discussion or a supplementary panel showing wind direction/speed at the observatory level would better contextualize the plume's arrival.

Authors: We thank the reviewer for this suggestion. In the manuscript, we focused on the meteorological conditions recorded at the Candelaria station rather than at the Izaña Observatory, as the atmospheric situation at the onset of the wildfire was particularly relevant to the ignition phase. In contrast, the subsequent spread of the fire, which became very extensive across the island (more than 13000 hectares), was influenced by additional factors. In the insular context of Tenerife, the fire propagation was strongly related to the severe water stress of the vegetation following several months of very limited precipitation and persistent dryness. In addition, the frequency of typical trade-wind conditions during that period was unusually low. These trade winds normally help maintain a cooler and more humid environment in the forested areas, and their reduced occurrence likely contributed to the enhanced dryness of the vegetation and favoured the fire spread.

Plume Proximity: The manuscript states the fire occurred "only a few metres" from the spectroradiometer. Please provide a more precise estimate of the distance to the active fire front during the 17–18 August peak to support the "near-source" characterization.

<u>Authors:</u> The distance between the active fire front and the Izaña Observatory during the peak period from 17 to 18 August was approximately 270 meters to the North. The following figure shows the evolution of the affected area between the 17th and 18th of August 2023, resulting from pyrocumulonimbus activity over the extended burned areas of Tenerife (Canary Islands), based on the Copernicus Emergency Management Service Rapid Mapping analysis (<u>https://rapidmapping.emergency.copernicus.eu/EMSR686</u>, last access: 15 April 2024).

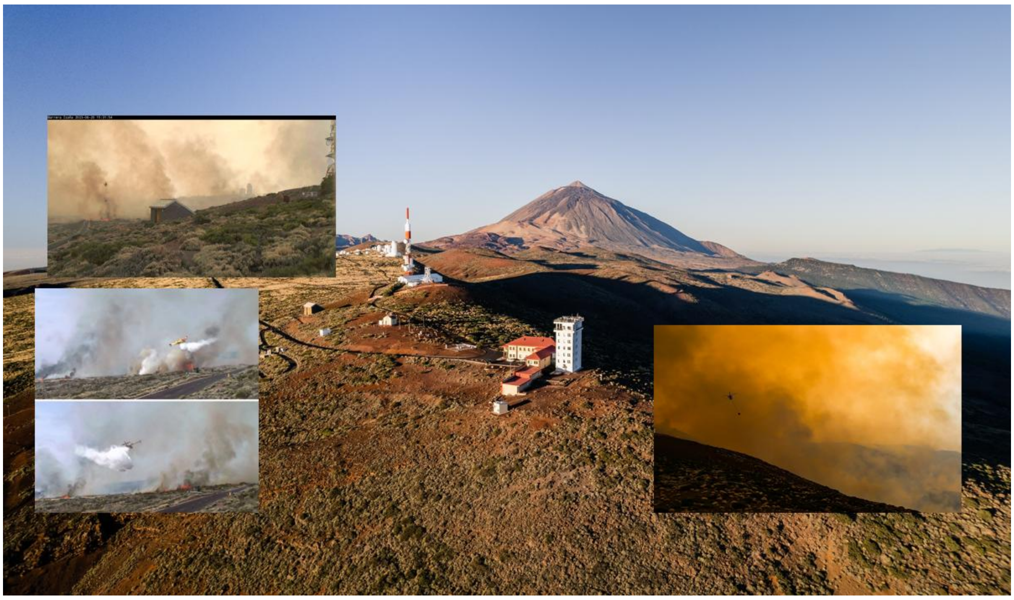


This distance has been added at the final manuscript as follows:

> *"...The extreme 2023 fire episode occurred **only ≈280 m north and 620 m east of** the spectroradiometer operating at IZO, providing a unique opportunity to directly observe the spectral radiative signal of fresh smoke under near-source conditions."*

Plume Height: You mention that the fresh smoke layer extended up to 4 km a.s.l. based on lidar observations. Given that the Izaña Observatory is located at 2400 m a.s.l., please explicitly discuss the fact that the observatory was effectively immersed within the smoke plume. This is crucial for interpreting the extremely high surface concentrations.

<u>Authors:</u> The authors have no doubt that the Izaña Observatory was enveloped by the smoke plume. This is also demonstrated by the different techniques used throughout the manuscript to corroborate this finding, including both column-integrated and in situ measurements. The following figure shows the location of the different instruments used in this study and their close proximity to each other.



2. Clarification of Measurement Levels (Sections 2.3.3, 2.3.4, and 2.3.5)

It should be explicitly stated in the headings or introductory sentences of these sections that the TEOM , MAAP , and Integrating Nephelometer measurements represent ground-level (in-situ) concentrations at the observatory.

Authors: *Done*

These surface-level observations should be discussed in direct relation to the plume height mentioned earlier (4 km a.s.l.) to clarify that these are not column-integrated values but point measurements within the plume layer.

Authors: The authors understand that some confusion may arise from the description of the event due to the combination of remote sensing and in situ techniques. For this reason, we have added an introductory sentence at the beginning of line 248*:*

> *“**This local event was also characterised using in situ surface measurements, complementing remote-sensing observations**. PM10 and PM2.5 concentrations experienced…”*

After this line, in situ surface measurements are described up to line 264, where a direct comparison between in situ and column-integrated results becomes necessary (acknowledging the intrinsic complications associated with this type of comparison). In particular, we believe that the information explicitly referred to by this referee corresponds to the text between lines 273 and 277. We have modified this paragraph to clarify this distinction:

> *“…**The consequence of this pronounced aerosol layering above the station is that surface observations detected the arrival of smoke-dominated air masses, whereas column-integrated observations indicated the dominance of coarser desert dust particles.**”*

3. AERONET Data and Retrieval Limitations (Lines 116–121)

Data Levels: The manuscript clarifies that Level 2.0 data was used for 17 August, but Level 1.0 was required for 18 August because the extreme aerosol load was misclassified as clouds by the AERONET algorithm. This has been done in other studies as well, when we "know" that the cloud flagging is off. But some discussion on the uncertainties introduced by this choice should be provided.

Authors: As is well known, Version 3 Level 1.5 represents near-real-time automatic cloud screening and automatic instrument anomaly quality control, including several procedures designed to detect not only clouds but also potential instrument anomalies. Pre-field and post-field calibrations, as well as temperature characterisation, are applied only when the data reach Level 2.0. This means that quality assurance is guaranteed only for Level 2.0 data. This information will never be accessible to the station in the case that the measurements were erroneously filtered, as is the case in the present study. There are many examples in the literature showing that the quality control procedures implemented operationally within the AERONET algorithm can fail under extreme circumstances, as was the case for the events described in this study.

Since it is impossible to compare products that were not generated, and the specific reasons why the different steps of the complex automatic quality control implemented in AERONET Version 3 failed are also unknown, the only way to truly assess the consistency of the measurements from both events is to perform an intercomparison with another independent instrument that measured during both events: the EKO MS-711 grating spectroradiometer, which was measuring simultaneously with the Cimel during the two events. The results show a high level of consistency between the measurements from both instruments during the two events, ruling out the presence of any instrumental problem or anomaly in the Cimel that could have led to the rejection of these data by the quality control algorithm (see Figure).

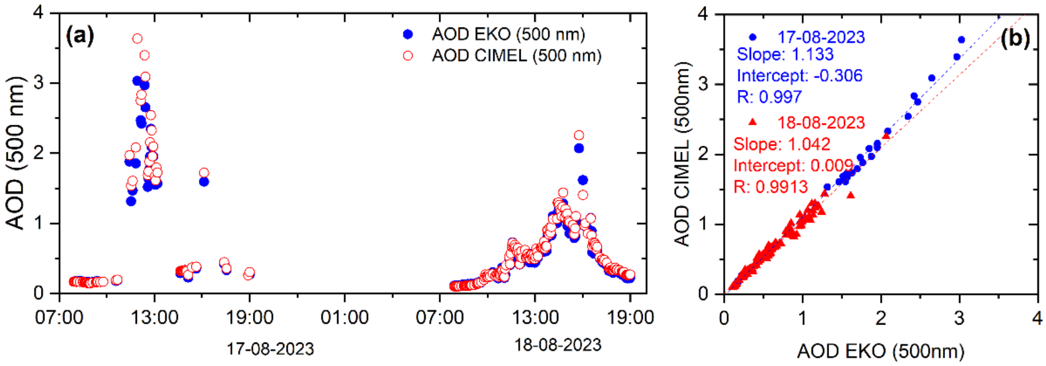


Figure.- (a) Time series of aerosol optical depth (AOD) at 500 nm measured by EKO (blue) and CIMEL (red) instruments on 17–18 August 2023. (b) Scatterplot AOD measured by CIMEL versus AOD EKO, including linear regression fits for each day.

Methodological Limitations: Please expand the discussion on the limitations of AERONET retrievals during such extreme events. Specifically, how does the use of Level 1.0 data (without final calibration or full quality control) impact the uncertainty of the AOD and AE values presented in Table 1?

Authors: As described above, the authors have presented arguments to ensure that the measurements performed during the first event (Level 1.0) were not affected by any instrumental issues that could compromise their quality. What has not been clarified until this point is the extent to which these Level 1.0 AOD values may differ from those measured the following day (Level 2.0) as a result of post-processing related to calibration drift during station operation. Considering that the calibration drift observed in photometers—such as the reference photometers of the network operated at Izaña—is expected to be low (on the order of 2%). In the specific case of the AERONET photometer used in this study, the mean inter-channel variation amounts to only 0.27%. Taking into account that the information presented in this section is used solely for a qualitative description of the event, we consider that the impact of this assumption does not have a direct consequence on the objective of the study, which is to investigate the impact of Spectral Aerosol Radiative Forcing at our station during a specific event.

Cloud Flagging: Could you specify if the Level 1.0 data points used were those specifically flagged as "cloudy" in the standard Version 3 algorithm? Confirming that these "clouds" were actually the dense wildfire plume would strengthen the justification for using Level 1.0 data.

Authors: As stated previously, the authors do not have information on the specific reasons why the various steps of the complex automatic quality control implemented in AERONET Version 3 failed for the near-real-time Level 1.5 AOD products. However, the high level of consistency between the EKO and Cimel measurements shown above rules out any instrumental problem or anomaly in the Cimel that could have led to the rejection of these data by the quality control algorithm, ensuring the presence of clouds (from fire) as the reason for rejecting this data.

4. **Inversion Products and SSA Hypothesis.**

The authors state that inversion products (SSA and asymmetry parameter) were unavailable due to insufficient data, which is very reasonable given the non homogenity of the skies during the event.

Since spectral Single Scattering Albedo (SSA) significantly influences the final radiative effect, please discuss in detail the specific hypotheses or fixed values used for these parameters in your radiative transfer simulations.

A sensitivity analysis or a comparison with literature-based SSA values for fresh biomass-burning smoke (e.g., from the referenced 2021 Greece fires) would add robustness to the radiative forcing calculations.

Authors: *In this study, the radiative forcing due to the presence of the wildfire smoke plume was determined using the equation:*

$$\Delta F(\lambda, SZA) = F^{\downarrow A}(\lambda, SZA) - F^{\downarrow C}(\lambda, SZA)$$

where $F^{\downarrow A}$ *represents the downward irradiance at the surface in the presence of atmospheric aerosols, while* $F^{\downarrow C}$ *corresponds to the irradiance expected under clean or pristine atmospheric conditions, obtained from radiative transfer simulations. Therefore, the SSA values are not taken into account in the simulations.*

The influence of the SSA and sensitivity analysis or a comparison with literature-based SSA values for fresh biomass-burning smoke is beyond the scope of this study. This will be addressed in a future study.

Impact of Spectral Aerosol Radiative Forcing at the Izaña Observatory during the August 2023 Extreme Wildfires.

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Abstract. Extreme wildfires represent a highly variable source of atmospheric aerosols with potentially strong impacts on surface solar radiation. In August 2023, an exceptional wildfire on Tenerife (Canary Islands, Spain) reached the neighbourhoods of the Izaña Observatory (IZO, 2400 m a.s.l.). This near-source configuration enabled a rare observational characterisation of the spectral radiative effects of biomass-burning aerosols. During the most intense phases of the event (17–18 August), aerosol optical depth (AOD) at 500 nm reached extreme values of 3.63 and 2.25, respectively, with Ångström Exponent (AE) above 2, indicating a strong dominance of fine-mode smoke particles. Spectral measurements of global-horizontal, direct-normal and diffuse-horizontal solar irradiance (300–1100 nm) show a pronounced attenuation of direct and global irradiances, particularly in the visible range, together with a strong enhancement of diffuse radiation. Relative to clean-sky conditions, daily global irradiance decreased by 21–27 %, while direct-normal irradiance was reduced by 72–99 %. Spectral aerosol radiative forcing and radiative forcing efficiency at the surface were quantified using radiative transfer simulations under pristine atmospheric conditions as a reference. The integrated spectral radiative forcing (300-1100 nm) for global irradiance reached -395 and -299 W m^{-2} on 17 and 18 August, respectively, indicating strong surface cooling dominated by scattering processes. Maximum forcing and efficiency occurred in the visible spectral range, consistent with the optical properties of freshly emitted smoke aerosols. At the same time, increases in the amount of present particles, equivalent black carbon (eBC) and greenhouse gases (CO_2, CH_4 and CO) confirm the direct influence of the wildfire plume on atmospheric composition at IZO. These observations provide one of the few detailed spectral assessments of surface radiative forcing by extreme biomass-burning aerosols at a high-altitude site and highlight the need to accurately represent fine-mode smoke aerosols in radiative transfer and climate models.

1 Introduction

Wildfires are increasingly recognised as key agents of changes on the atmosphere, influencing air quality, the planetary radiation budget, and the climate system. According to the IPCC Sixth Assessment Report (IPCC, 2023), the total anthropogenic effective radiative forcing in 2019 relative to preindustrial conditions is estimated at 2.72 [1.96–3.48] W m^{-2} (medium confidence) (Forster et al., 2021). This positive forcing arises mainly from the continuous accumulation of greenhouse gases (GHGs), partially offset by the cooling effect due to anthropogenic aerosols. IPCC (2023) also reports a $\sim$0.43 W m^{-2} ($\sim$19 %) increase in the total radiative forcing since the Fifth Assessment Report (IPCC, 2013). Most of this increment, around 0.34 W m^{-2}, is attributed to additional GHG emissions since 2011, while the remaining increase, around 0.09 W m^{-2}, reflects improved estimates of aerosol contributions, owing to enhanced observational datasets and progress in representing aerosol–radiation and aerosol–cloud interactions in climate models.

Among the different aerosol sources, biomass burning stands out as one of the most variable and least predictable in terms of emissions and radiative effects. Aerosols produced by wildfires encompass a heterogeneous mixture of absorbing components (e.g., black carbon, brown carbon) and scattering species (organic and inorganic matter). Their radiative influence depends strongly on their optical and microphysical characteristics, vertical distribution within the atmosphere, and interactions with clouds and underlying surfaces. These complexities generate significant uncertainty when assessing the radiative forcing associated with wildfire emissions.

In recent decades, wildfire activity has intensified across many regions of the globe, a trend strongly linked to rising global temperatures, a higher frequency of extreme heat events, and widespread transformations in land use and droughts (Cunningham et al., 2024; Elmqvist et al., 2025; WMO, 2023). Current estimates indicate that wildfires burn 3.5–4.6 million km^2 each year, equivalent to about 2–3 % of Earth's land surface (Guo et al., 2025). Beyond their ecological impacts, these events represent a major atmospheric source of trace gases and aerosols, with significant implications for air quality and climate. Areas with Mediterranean-type climates—such as southern Europe, California, central Chile, southwestern Australia, and parts of South Africa—are particularly prone to suffer large and intense fires due to their hot and dry summers, and strong interannual climatic variability. Within Europe, Mediterranean countries account for nearly 85 % of the total burned area (Sicard et al., 2012; Amatulli et al., 2013; Zhuravleva et al., 2017; San-Miguel-Ayanz et al., 2023). Recent high-impact fire seasons, including the 2016 Madeira fires (Navarro et al., 2017) and the 2023 wildfire crisis in Greece (Masoom et al., 2023; Michailidis et al., 2024; Koukouli et al., 2025), have highlighted the growing societal exposure to fire hazards, often resulting in mass evacuations, severe damage to infrastructures, and major economic losses (Jones et al., 2024; Elmqvist et al., 2025). At the same time, shifts in atmospheric circulation—particularly the increased frequency and intensity of extreme heatwaves and droughts—together with the desiccation of continental air masses, such as Saharan advection episodes, create highly favourable conditions for fire ignition and rapid fire spread. This is the case for one of the most frequent types of heatwaves over Europe, which often occur in the presence of intrusions of desert dust particles originating from North Africa (WMO, 2023). The Canary Islands (Spain) are regularly influenced by such Saharan intrusions, which constitute a prominent and recurrent component of the regional atmospheric dynamics (Cuevas et al., 2017; Barreto et al., 2022). These air masses are typically characterised by exceptionally low humidity and temperatures well above climatological values (Correa and Dorta, 2025).

In August 2023, a large-scale wildfire on Tenerife (Canary Islands) allowed researchers to investigate, as an exceptional natural experiment, the atmospheric impacts of intense biomass burning. It was the second largest wildfire on Tenerife and the third in the Canary Islands since systematic monitoring began in 1983 (Correa and Dorta, 2025). The fire burned more than 13.000 hectares across 12 municipalities and advanced, reaching the close vicinity of the Izaña Observatory (IZO), a high-mountain research station operated by the Spanish State Meteorological Agency (AEMET) through the Izaña Atmospheric Research Center (IARC). Although the observatory infrastructure was not damaged, the extreme closeness of the fire enabled direct observations of its impact in the low free troposphere. This unusual scenario provided a unique opportunity to examine how intense wildfire emissions affect a wide range of atmospheric parameters routinely measured at IZO. As part of the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) programme, and of the European Research Infrastructure Consortia ACTRIS (Aerosols, Clouds and Trace Gases Research Infrastructure) and ICOS (Integrated Carbon Observation System), IZO maintains long-term records of greenhouse gases, aerosols, solar radiation, and reactive gases, among other variables (Laj et al., 2024; Cuevas et al., 2023, 2024). During the wildfire episode, pronounced anomalies were detected across these datasets, offering valuable insights into the radiative and compositional impacts of smoke intrusions at this remote high-elevated site.

This study aims to characterise the spectral aerosol radiative forcing and efficiency exerted by wildfire aerosols. Such spectral studies are very scarce, and most existing works focus on the impact of wildfires on irradiance without considering their effects on radiative forcing or efficiency. The extreme 2023 fire episode occurred only a ~~few metres from~~ ≈ 280 m north and 620 m east of the spectroradiometer operating at IZO, providing a unique opportunity to directly observe the spectral radiative signal of fresh smoke under near-source conditions.

The measurements used in this study were conducted within the framework of the WMO Measurement Lead Centre (MLC) for Aerosols and Water Vapour Remote Sensing Instruments. The structure of the paper is as follows: Section 2 presents the main features of the Izaña Observatory and the instrumentation used in this work. Section 3 describes the methodology applied to quantify aerosol spectral radiative forcing and radiative efficiency. Section 4 provides an overview of the wildfire event and presents the key results. Finally, Section 5 summarises the main conclusions of the study.

2 Site description and instruments

2.1 Site description

The datasets analysed in this study were obtained at the Izaña Observatory (IZO), operated by the Izaña Atmospheric Research Center (IARC) of the Spanish State Meteorological Agency (AEMET) (http://izana.aemet.es, last access on 15 April 2025). IZO is located on the island of Tenerife (Canary Islands, Spain (28.3° N, 16.5° W)), at an altitude of 2400 m a.s.l. (Figure 1a), and is typically situated above a quasi-permanent temperature inversion layer. This persistent atmospheric feature limits the vertical transport of locally generated pollutants from lower altitudes, ensuring that the measurements collected at the site are

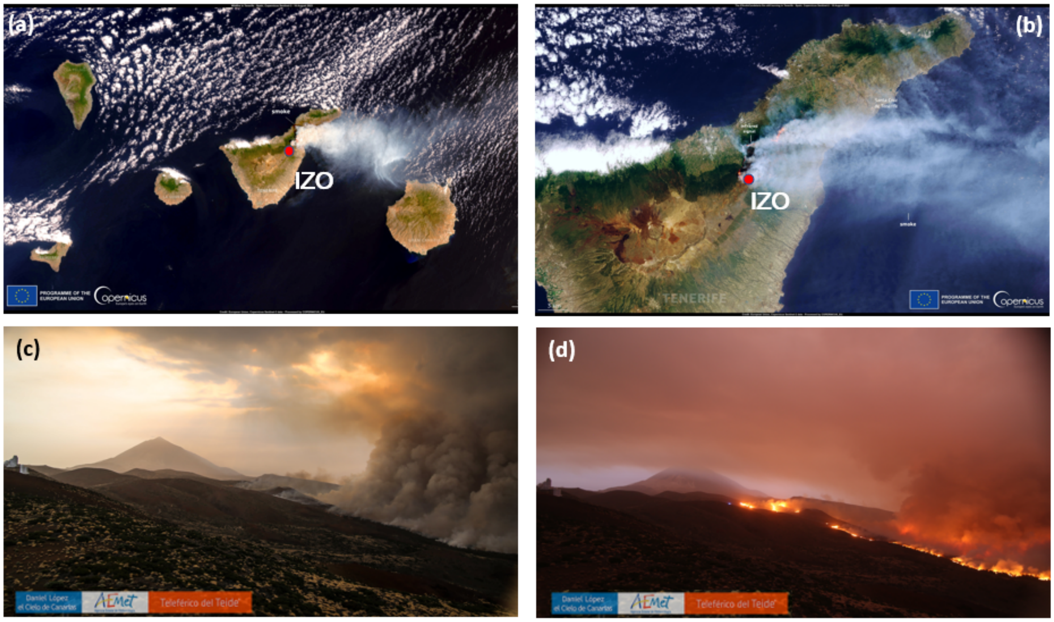

Figure 1. (a,b) Copernicus Sentinel-2 image acquired on 18 August over Tenerife. The red dot marks the location of the Izaña Observatory (Canary Islands, Spain). (c,d) Images of Teide National Park captured on 17 and 18 August 2023 from Izaña Observatory (Teide Cloud Laboratory Project, project from Izaña Observatory by Daniel López).

mostly representative of free-tropospheric conditions (Cuevas et al., 2013). Consequently, IZO offers an exceptional environment for both in situ and remote sensing observations of trace gases and aerosols. The combination of a stable total ozone column, extremely low water vapour content, reduced aerosol loading, and the frequent occurrence of clean, cloud-free skies makes the observatory an ideal reference site for calibration and validation activities (more details in Cuevas et al. (2024)).

2.2 Instruments

2.2.1 EKO RSB spectroradiometer

In this study, global (GHI_λ), direct-normal (DNI_λ), and diffuse (DHI_λ) spectral irradiance were measured using an EKO MS-711 spectroradiometer equipped with a rotating shadow band (hereafter EKO RSB; Figure 2a). The instrument operates over the 300–1100 nm range, with a spectral step of approximately 0.4 nm and a nominal full width at half maximum (FWHM) of less than 7 nm. It acquires one spectrum per minute, with exposure times automatically adjusted between 10 ms and 5 s according to irradiance levels and sky conditions. Each measurement cycle consists of four sequential acquisitions at different shadow band positions (Figure 2b), completed in less than one minute (Pó et al., 2018; Takamura and Khatri, 2021). Thus, at the 1^{st} position the shadow band rests outside the instrument's field of view (FOV); at the 2^{nd} position the shadow band stops at -5° from the solar disk; at the 3^{rd} position the EKO RSB covers the solar disk to perform the diffuse measurement and

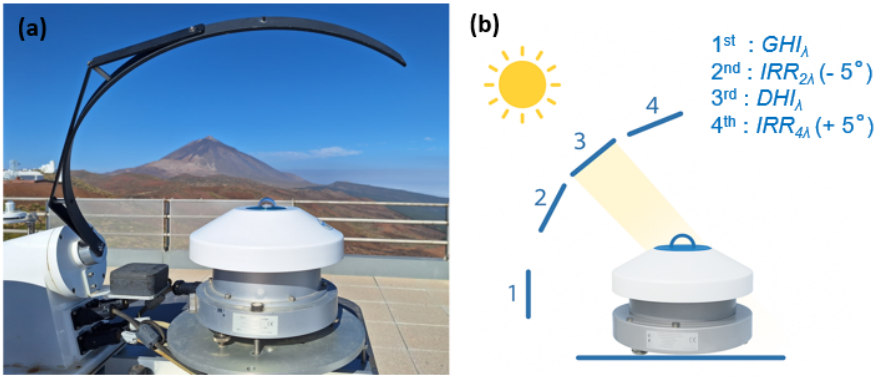

Figure 2. (a) The EKO RSB grating spectroradiometer installed at Izaña station. (b) EKO RSB band sweeping positions (Figure adapted from Pó et al. (2018))

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finally at the 4^{th} position the shadow band stops at +5° ~~after~~ beyond the solar disk. The spectral GHI_λ and DHI_λ irradiances are measured in the 1^{st} and 3^{rd} positions, respectively. From these two measurements, the DNI_λ spectral irradiance is derived as follows:

$$DNI_\lambda = \frac{(GHI_\lambda - DHI_\lambda)}{cos(SZA)} \tag{1}$$

where SZA is the solar zenith angle. The 2^{nd} ($IRR_{2\lambda}$) and 4^{th} ($IRR_{4\lambda}$) positions are used to estimate the amount of diffuse irradiance lost due to the EKO RSB's partial obstruction of the sky, and a correction is applied to DHI_λ as follows:

$$DHI_{\lambda corr} = DHI_\lambda + (GHI_\lambda - \frac{IRR_{2\lambda} + IRR_{4\lambda}}{2}) \tag{2}$$

2.3 Ancillary instruments

2.3.1 AERONET Cimel Sun Photometer

The aerosol columnar optical properties (aerosol optical depth (AOD), Ångström Exponent (AE), and fine/coarse AOD) used in this study were obtained from measurements performed with a Cimel CE318-T sun–sky–lunar photometer, the reference instrument of the AErosol RObotic NETwork (AERONET), a global federated network established in 1993 for the long-term monitoring and characterization of atmospheric aerosols (Holben et al., 1998; O'Neill et al., 2003; Barreto et al., 2016; Giles et al., 2019; O'Neill et al., 2023). This instrument is an automatic scanning filter radiometer operating at nine nominal wavelengths (340, 380, 440, 500, 675, 870, 937, 1020, and 1640 nm), with a FOV of 1.3° (Holben et al., 1998; Torres et al.,

2013) and a FWHM of 10 nm, except for 340, 380, and 1640 nm, which have bandwidths of 2, 4, and 25 nm, respectively. Izaña Observatory is an AERONET calibration site for reference instruments (Toledano et al., 2018).

In this study, Level 2.0 AERONET direct-sun products (AOD, AE, and fine/coarse AOD) were used to retrieve aerosol properties for 17 August. However, for 18 August, Level 1.0 AOD data were employed because the extreme intensity of the event caused most photometric measurements to be misclassified as cloudy by the AERONET quality-control algorithms, as previously reported for the February 2020 desert dust outbreak (Cuevas et al., 2021). To ensure retrievals under clear-sky conditions, only measurements identified as clear sky by the procedure of Long and Ackerman (2000), as adapted for Izaña by García et al. (2014), were considered. Furthermore, inversion products (such as single scattering albedo and asymmetry parameter) were not used because the available data were insufficient for this study.

2.3.2 Micro-Pulse Lidar

Relative attenuated backscatter profiles and volume depolarization ratios were measured with a Micro-Pulse Lidar (MPL, model MPL-4B) operating at IZO during the forest fire outbreak at the station. This type of lidar is an eye-safe elastic lidar operating continuously (24/7) at 532 nm with a low-pulse energy laser (5–6 μJ) and a repetition rate of 2.5 kHz (Welton et al., 2001; Campbell et al., 2002). The MPL-4B version features depolarization capability, which is useful for identifying depolarizing particles (Flynn et al., 2007). As the reference instrument of the National Aeronautics and Space Administration Micro-Pulse Lidar Network (NASA-MPLNet), signal processing and retrieval products are centralised at the network level (Welton et al., 2018). According to Campbell et al. (2002) and Welton et al. (2018), this processing includes corrections for detector deadtime and dark current, laser–detector after-pulse, overlap, and polarization calibrations. MPLNet Version 3, Level 1.5 aerosol products were used in this study.

2.3.3 TEOM

~~Bulk~~ Surface measurements of bulk mass concentrations were measured using the TEOM 1405-DF instrument (Thermo Fisher Scientific^{TM}). This instrument operates by collecting particles onto a vibrating substrate maintained at constant amplitude. As particles accumulate on the filter, the increasing mass causes a decrease in the vibration frequency. The total particle concentration (PM, Particulate Matter) is then calculated from this frequency change as a function of aerosol mass accumulation over time (Patashnick et al., 1983).

The TEOM 1405-DF measures the coarse PM and $PM_{2.5}$ fractions of PM_{10}, which are separated by a virtual impactor and collected on two dedicated filters. PM_{10} concentration is obtained by summing the $PM_{2.5}$ and coarse PM fractions. The instrument has a resolution of approximately ±5 μg m^{-3} for 10-minute sampling intervals (Rodríguez et al., 2012).

2.3.4 ~~MAPP~~MAAP

Surface Equivalent Black Carbon (eBC) mass concentrations were obtained from two Multi-Angle Absorption Photometer instruments (MAAP; Thermo^{TM}) with separated sampling lines for PM_{10} and PM_1 using virtual impactors. MAAP instruments measure the change in transmittance of a 637 nm light source through a filter tape as particles are deposited. Additionally, the instrument measures backscattered light from the sample and filters using two detectors positioned at different angles. This configuration enables determination of the absorption of the aerosol sample through a radiative transfer scheme with a relative uncertainty of $\pm 12\%$ (Petzold and Schönlinner, 2004). The measured absorption is then converted to eBC mass concentration using a mass absorption cross-section of 6.6 m^2 g^{-1}, defined in the instrument firmware following ACTRIS guidelines (Müller et al., 2011; Petzold et al., 2013).

2.3.5 Integrating Nephelometer

~~Total~~ Surface total scattering coefficient data (σ_{scat} (λ)) were collected with a TSI^{TM} integrating nephelometer (model 3563) at three wavelengths (450, 550, and 700 nm). From that, the Scattering Ångström Exponent (SAE; Ångström (1930)) was calculated using the 450 (λ_1) nm and 700 (λ_2) nm total scattering values according to the following relation:

$$SAE = -\frac{ln(\sigma_{scat}(\lambda_1)/\sigma_{scat}(\lambda_2))}{ln(\lambda_1/\lambda_2)} \tag{3}$$

The instrument is calibrated annually using CO_2 as the high span gas and filtered air as the low span gas. The averaging time is set to 1 minute, and the instrument performs routine 5-minute zero checks every hour. Additional corrections for truncation and non-Lambertian illumination were applied to the data following the method described by Anderson and Ogren (1998), which gives a reported uncertainty of approximately 7 % for scattering values (Heintzenberg et al., 2006). Sampling is performed through an inlet assembly with a PM_{10} virtual impactor.

The Single Scattering Albedo (SSA; ω_0) was calculated following Valenzuela et al. (2015), by combining the total scattering coefficient ($\sigma_{scat}(\lambda)$) from the nephelometer and the absorption coefficient ($\sigma_{abs}(\lambda)$) derived from the MAAP measurements. The absorption coefficient was obtained by multiplying the eBC mass concentration by the mass absorption cross-section of 6.6 m^2 g^{-1}, with a correction factor of 1.05 applied to account for the shift in the MAAP light source wavelength (Müller et al., 2011). SSA was then computed at 637 nm using:

$$\omega_0(\lambda) = \frac{\sigma_{scat}(\lambda)}{\sigma_{scat}(\lambda) + \sigma_{abs}(\lambda)} \tag{4}$$

where σ_{scat} (λ) was interpolated to 637 nm from the nephelometer measurements using the SAE, in order to match the MAAP absorption wavelength.

All in situ aerosol measurements were conducted in the same laboratory, under controlled environmental conditions, with ambient temperature maintained at 21 ± 2 °C. Data points were subsequently filtered to exclude measurements recorded at relative humidity above 40 % to ensure dry sampling conditions.

2.3.6 Picarro Cavity Ring-Down Spectrometer

Dry-air mole fractions of CO_2, CH_4, and CO were measured using a Picarro G2401 analyser based on cavity ring-down spectroscopy (Crosson, 2008). The analyser operates continuously at IZO under the WMO-GAW programme (Cuevas et al., 2024) and is calibrated monthly using four multi-species tertiary standards prepared by the WMO Central Calibration Laboratory (https://gml.noaa.gov/ccl/, last access on 25 November 2025). Measurements are reported on the following WMO scales: X2019 for CO_2, X2004A for CH_4 and X2014A for CO. The system provides high-precision measurements with typical 1σ uncertainties for 1-minute averages of 0.013 ppm (CO_2), 0.19 ppb (CH_4), and 0.87 ppb (CO) when analysing calibration tanks (Gómez-Pelaez et al., 2019).

Ambient air is sampled from the roof of the IZO building and passed through a cold trap at -70 °C to remove water vapour and ensure dry-air conditions. The instrument acquires data every 2 seconds, but in this study we used 1-minute averaged values. Further details on the calibration procedure and instrument characterisation can be found in Gómez-Pelaez et al. (2019).

3 Methodology: Spectral radiative forcing and efficiency

To quantify changes in the energy budget of the Earth–atmosphere system, the concept of radiative forcing (ΔF) is introduced as an indicator of these changes (IPCC, 2023). In this study, we focus on the aerosol effect, particularly that associated with biomass burning. The radiative forcing (ΔF) is defined as follows, considering its dependence on wavelength and solar zenith angle:

$$\Delta F^{\mathrm{eff}}(\lambda, SZA) = \frac{\Delta F(\lambda, SZA)}{\mathrm{AOD}(\lambda, SZA)} \tag{5}$$

In this equation, $F\downarrow^{A}$ represents the downward irradiance at the surface in the presence of atmospheric aerosols, while $F\downarrow^{C}$ corresponds to the irradiance expected under clean or pristine atmospheric conditions, obtained from radiative transfer simulations. Under this sign convention, negative values of ΔF(λ,SZA) indicate a cooling influence of aerosols at the surface, whereas positive values denote a warming effect.

After computing ΔF(λ,SZA), the spectral aerosol radiative forcing efficiency, ΔF^{eff}(λ,SZA), can be defined as:

$$\Delta F^{\mathrm{eff}}(\lambda, SZA) = \frac{\Delta F(\lambda, SZA)}{\mathrm{AOD}(\lambda, SZA)} \tag{6}$$

where AOD(λ,SZA) represents the aerosol optical depth at the specified wavelength and solar zenith angle, which in this case was obtained from direct-normal spectral irradiance measurements (DNI_λ) recorded by the EKO RSB following the methodology described in García et al. (2020).

To estimate $F^{\downarrow C}$(λ,SZA), the libRadtran radiative transfer model was used (Mayer and Kylling, 2005; Emde et al., 2016). This model has been extensively tested at the Izaña Observatory (e.g. García et al. (2014); García et al. (2019); García et al. (2020)). The radiative transfer equation (RTE) solver employed was the DIScrete Ordinates Radiative Transfer (DISORT) algorithm (Stamnes et al., 1988), which is based on a multi-stream discrete ordinates method using 16 streams. Corrections for Earth's sphericity were applied for SZA greater than 70° (Dahlbäck and Stammes, 1991). For each simulation, the GHI_λ, DNI_λ and DHI_λ spectral irradiances were computed in the 300–1100 nm range with a 1 nm spectral step (García et al., 2023; Cachorro et al., 2025).

The forcing (ΔDF) and radiative forcing efficiency (ΔDF^{eff}) in different spectral ranges have been determined from the following equation:

$$\Delta DF = \int_{\lambda_1}^{\lambda_2} \Delta F(\lambda, SZA) \cdot d\lambda \tag{7}$$

4 Results

4.1 Description of the event

In August 2023, an extensive wildfire on the island of Tenerife provided a unique natural laboratory for investigating the atmospheric effects of biomass-burning aerosols. Although IZO remained physically unaffected by the fire, its proximity to the burning area offered an exceptional opportunity to monitor the resulting smoke plume and examine its evolution under free-tropospheric conditions. This situation enabled the direct characterisation of the optical, microphysical and radiative properties of wildfire-derived aerosols, thus yielding valuable insight into their short-term influence on the regional radiation budget and atmospheric composition.

Climatic conditions in the Canary Islands during August 2023 created a highly favourable environment for wildfire development. According to AEMET (AEMET, 2024), this month was exceptionally dry, with a mean temperature of 25.4 °C and a positive anomaly of +2.3 °C compared to the 1991–2020 reference period, ranking as the warmest August since 1961. A heatwave between 10 and 14 August (AEMET, 2023) pushed temperatures close to 40 °C, while relative humidity fell below 20 % and wind gusts exceeded 30 km h^{-1} in Tenerife, as recorded at the AEMET station in Candelaria (463 m a.s.l.), near to the origin point of the subsequent wildfire. Although the fire ignited one day after the maximum alert had been lifted-coinciding with notably milder conditions (27.3 °C maximum temperature; 75 % minimum humidity, Correa et al. (2025)), the severe desiccation of the forest fuel over prior weeks was decisive in enabling its rapid spread. Supporting this, the base of the subsidence-induced thermal inversion remained below 600 m a.s.l. from 11 to 19 August, maintaining a warm and dry free troposphere above the island (Correa and Dorta, 2025; Correa et al., 2025).

During the period 15–31 August 2023, a pronounced aerosol episode was detected at IZO on 17 and 18 August (Figure 1 c, d and Figure 3). The AOD values increased sharply across all measured wavelengths (340–870 nm), reaching maxima of 4.81 and 3.63 at 340 and 500 nm, respectively, on 17 August, and 4.10 and 2.25 at 340 and 500 nm, respectively, on 18 August. Simultaneously, AE>2 on both days (2.06 on 17 August and 2.04 on 18 August) (see Table 1), indicating a predominance of fine-mode particles. These features are characteristic of biomass-burning aerosol intrusions and are comparable to those

Table 1. Aerosol optical and microphysical properties corresponding to the maximum of AOD$_{500nm}$ values performed at IZO on 17 and 18 August 2023. Parameters included are: AOD (500 nm), AE (440–870 nm), Total (500 nm), Fine (500 nm), and Coarse-mode (500 nm), fine-mode fraction (FMF, 500 nm), mass concentration of PM$_{10}$ (μg m^{-3}) , ratio between PM$_{2.5}$ and PM$_{10}$, and the SAE (450–700 nm)

Case	SZA (°)	AOD	AE	Total	Fine	Coarse	FMF	PM$_{10}$	PM$_{2.5}$/PM$_{10}$	SAE
17-08-2023 11:56	22.7	3.63	1.71	3.61	3.58	0.03	0.99	393.17	0.81	1.78
18-08-2023 15:46	39.1	2.25	2.04	2.24	2.12	0.13	0.94	91.66	0.66	2.14

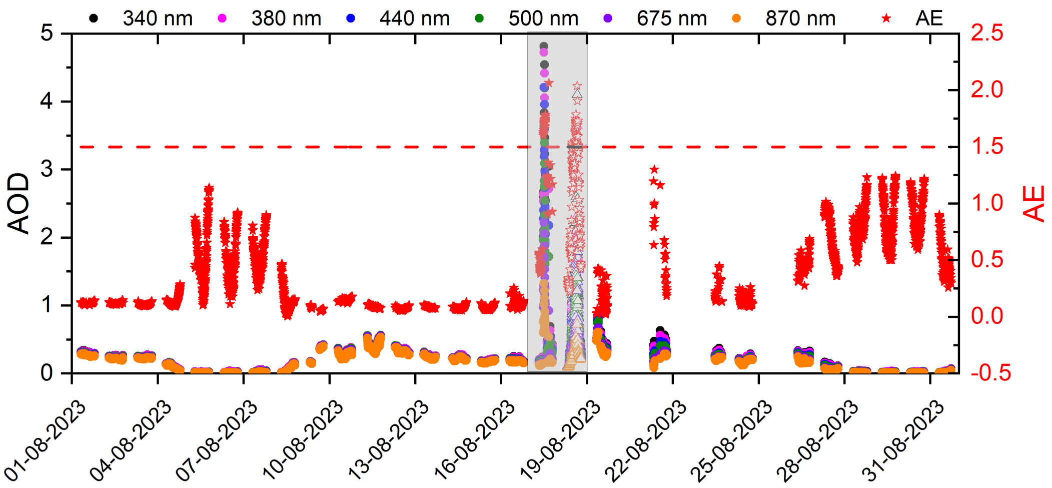

Figure 3. Time series of AOD at different wavelengths (left axis: 340 nm, black dots; 380 nm, magenta dots; 440 nm, blue dots; 500 nm, green dots; 675 nm, violet dots; and 870 nm, orange dots) and AE (440–870 nm) (right axis, red stars) during August 2023 at IZO. The red dashed lines and green area indicate the thresholds defined for biomass-burning conditions (AE > 1.5). The data are from the AERONET network, filled symbols correspond to Version 2.0 data, while open symbols represent Version 1.0 data.

reported by Masoom et al. (2023) during the extreme wildfire episode in Greece in August 2021, where AOD values up to 3.6 at 500 nm~~and~~ , AE up to 2.4 (440–870 nm), and fine-mode fractio (FMF) values around 0.98 were observed. Therefore, the following study focuses on the events recorded on 17 and 18 August.

A more detailed characterisation of the aerosol optical and microphysical properties during this episode is presented in Figure 4. Spectral AOD and AE evolution is presented in Figure 4a. The AOD decomposition at 500 nm during the event (Figure 4b) shows that the fine-mode component dominated the total column, with the ~~fine-mode fraction (FMF)~~ FMF approaching unity. On 17 August, the high AE and FMF values (∼1.5 and >0.8, respectively) indicate a fine-mode–dominated aerosol population, typical of freshly emitted smoke. As the event evolved (18–19 August), AE decreased below 0.8 and FMF below 0.4, revealing aerosol mixing with coarse dust particles within the plume. Figure 4c confirms this dominance, with data points from 17 and 18 August clustering in the region of high AE (> 1.5) and high FMF (> 0.8) (Figure 4c), indicative of fine-mode aerosols from biomass burning (Eck et al., 2001; O'Neill et al., 2023). These values are similar to those reported

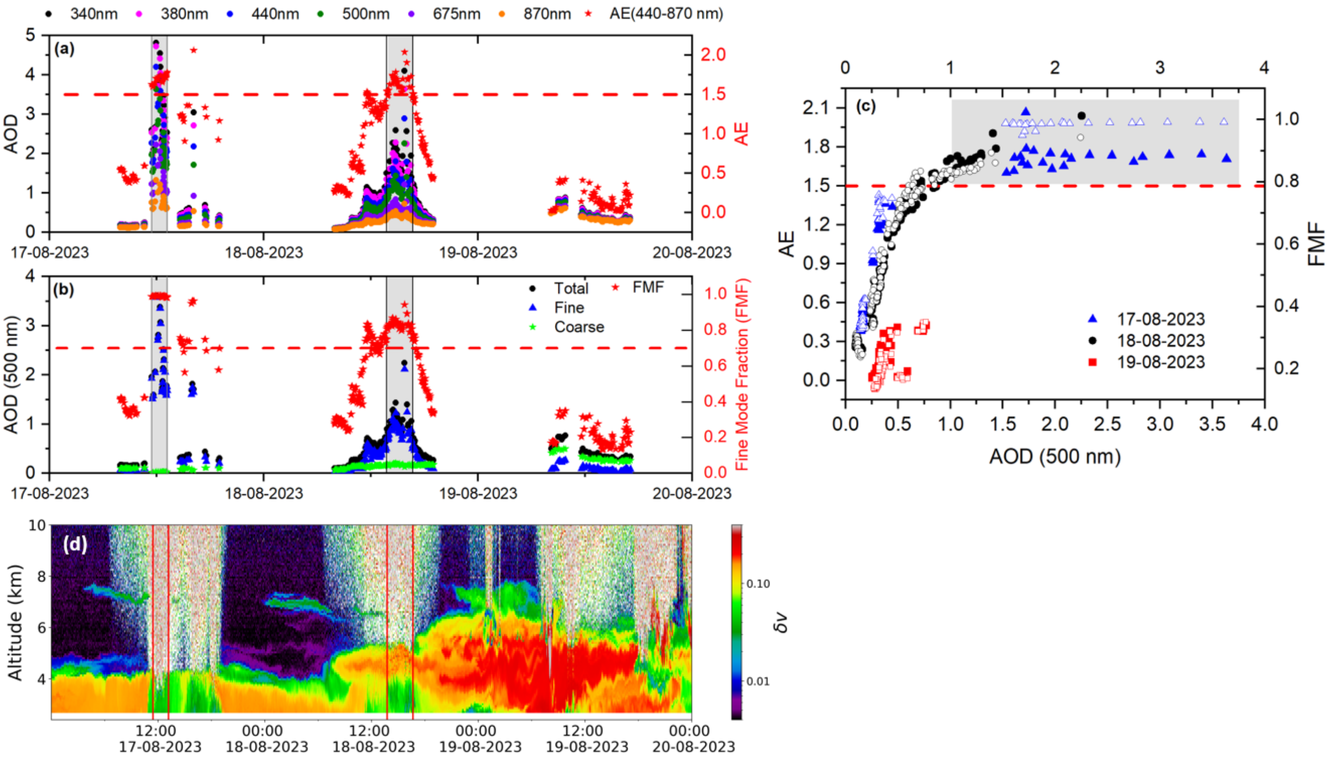

Figure 4. Time series of (a) AOD at different wavelengths (left axis: 340 nm, black dots; 380 nm, magenta dots; 440 nm, blue dots; 500 nm, green dots; 675 nm, violet dots; and 870 nm, orange dots) and AE (440–870 nm) (right axis, red stars); (b) total (black dots), fine-mode (blue triangles), and coarse-mode (green stars) AOD at 500 nm (left axis), together with FMF (right axis, red stars). Grey shaded areas highlight the two most notable fire events. (c) Scatterplot of AE versus AOD at 500 nm (filled symbols) and FMF versus AOD at 500 nm (open symbols) between 17 and 19 August 2023. The grey shaded area marks the thresholds defined for biomass-burning conditions (AE > 1.5 and AOD_{500nm} > 1.0). The data are from the AERONET network, Version 3, Level 1.5 for 17 and 19 August, and Level 1.0 for 18 August. (d) Temporal evolution of Volume Depolarization Ratio (δv) measured between 17 and 19 August with MPL-4B Lidar at IZO.

by ~~Masoom et al. (2023)~~ Masoom et al. (2023); Michailidis et al. (2024) for the extreme wildfires that occurred in Greece in August ~~2021.~~ 2021 and 2023, respectively, as well as to those reported by Filonchyk and Peterson (2024) at the El Arenosillo site in southern Europe as a result of the 2023 Canadian forest fires.

The vertical distribution of aerosols derived from lidar observations (Figure 4d) reveals that the fresh smoke layer extended up to 4 km a.s.l. on 17 and 18 August, with enhanced backscatter coefficients (not shown) and low volume depolarization ratios (δv) of 0.05–0.10 during the most intense fire periods (grey areas in Figure 4). For the 17 August event (no product available for 18 August), δp values ranged from 0.05 to 0.12. These values are consistent with those reported by Nepomuceno Pereira et al. (2014); Haarig et al. (2018) for fresh smoke, who found δp values around 0.05. According to these authors, such low δp

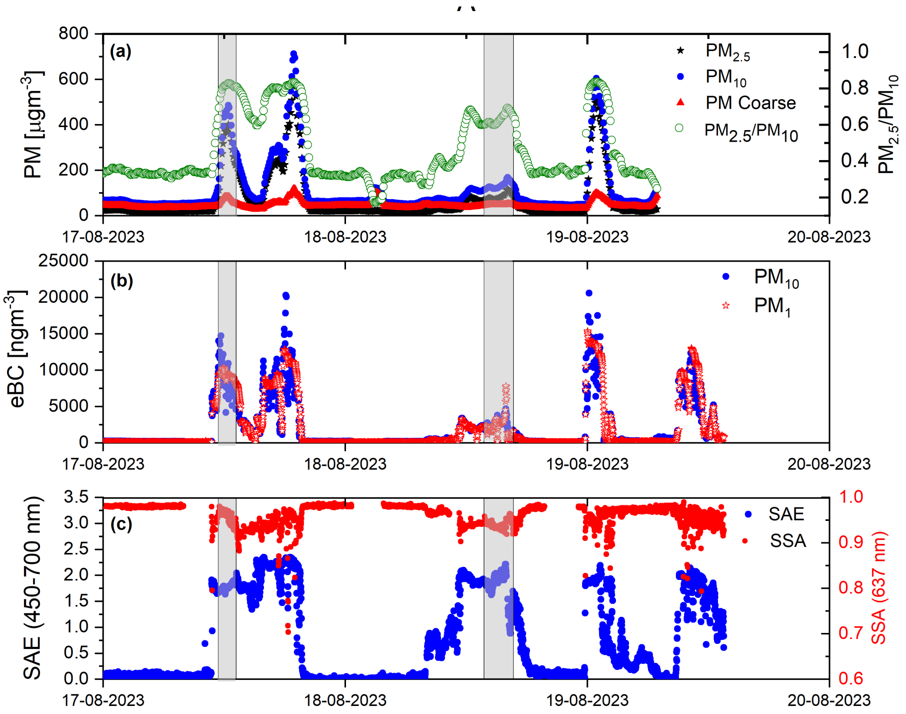

Figure 5. Time series of in situ aerosol measurements at IZO from 17 to 20 August 2023. (a) Mass concentrations of PM_{10} (black stars), $PM_{2.5}$(blue circles), ~~and~~ coarse-mode PM (red triangles) and $PM_{2.5}/PM_{10}$ ratio (green dots, right axis). (b) Equivalent Black Carbon (eBC) concentrations for PM_{10} (blue circles) and PM_1 (red stars) ~~and~~ (c) SAE (450–700 nm; blue circles) and ~~$PM_{2.5}/PM_{10}$ ratio~~ SSA (at 637 nm; red ~~dots~~circles, right axis). Shaded areas indicate the periods corresponding to the maximum AOD values observed on 17 and 18 August.

values indicate the dominant presence of spherical particles, mainly composed of a solid soot core coated with a liquid sulfate shell (Haarig et al., 2018).

An elevated layer reaching 7–8 km a.s.l. appeared on 19 August, characterised by high δv and δp values (up to 0.34 and 0.36, respectively), corresponding to the Saharan dust plume transported to IZO. The influence of coarse mineral dust particles is also consistent with the low AE values observed in Figures 4a, 4b, and 4c. After 19 August, both AOD and backscatter intensity decreased rapidly, marking the end of the episode. These results agree with those reported by González et al. (2025), who found similar values for both fresh aerosols from the same fire event and for mineral dust measured at Izaña using a dual-wavelength depolarisation elastic lidar (Cimel CE376). This elevated layer reached the altitude of Izaña between 05:00 and 09:00 UTC on 19 August and again after 12:00 UTC on the same day.

~~During this local event ,~~ This local event was also characterised using in situ surface measurements, complementing remote-sensing observations. PM_{10} and $PM_{2.5}$ concentrations experienced a substantial increase compared to their typical levels. In particular, PM_{10} and $PM_{2.5}$ (Figure 5a) reached peak concentrations of 712.19 and 594.64 μg m^{-3}, respectively, representing an increase of approximately 700 μg m^{-3} above typical values for the station (Rodríguez et al., 2011).

Five significant peaks were identified in the time series (Figure 5), with one peak excluded from TEOM data (Figure 5a) due to relative humidity filtering (Section 2.3). These peaks occurred on three consecutive days: two on 17 August (late morning and afternoon), one on 18 August afternoon, and two on 19 August, one at midnight and the other encompassing from the morning to midday. The peaks on 17 August morning and 18 August afternoon (shaded areas in Figure 5) coincided with fire events identified from columnar properties (Figure 4). The elevated PM_{10} and $PM_{2.5}$ concentrations ~~during these events~~ within these periods indicate direct impacts from wildfire smoke plumes at the observatory, reaching maximum values of 485.19 and 167.80 μg m^{-3} for PM_{10} and 401.53 and 116.26 μg m^{-3} for $PM_{2.5}$ (17 and 18 August). The eBC concentrations reached record values for the station (González et al., 2025) with peaks of 14.74 and 10.31 μg m^{-3} for the PM_{10} and PM_1 size cuts on 17 August, and 4.69 and 7.81 μg m^{-3} on 18 August. ~~The SAEand~~ Correspondingly, the SAE, $PM_{2.5}$/PM_{10} ratio~~provided~~, and SSA, which provide complementary information on aerosol size ~~distribution, with SAE values of 2.34 and 2.21, and $PM_{2.5}$/PM_{10} ratios of~~ and optical properties, reached maximum values of 1.93, 0.83~~and 0.69 for~~, and 0.98 on 17 ~~and~~ August, and 2.21, 0.69, and 0.96 on 18 August, respectively. These values collectively confirm the dominance of fine, light-scattering wildfire-originated particles during the selected events.

The temporal evolution of ~~the event~~ ground-level measurements from 17 to 20 August (Figure 5), revealed the successive entrance and exit of smoke-dominated air masses. Their progressive mixing with desert dust was reflected by oscillations in the $PM_{2.5}$/PM_{10} ratio from ∼0.8 to ∼0.3, accompanied by a decrease in the SAE from values above 2 to below 0.2. This behaviour was also evident in columnar-integrated measurements on 17 and 18 August. In contrast, the comparison between column-integrated and in situ measurements on 19 August revealed several complications. First, the midnight event could not be measured in the atmospheric column due to the limited availability of lunar photometry data, which is only available between the first and last quarters of the lunar cycle (Barreto et al., 2016). Second, it is important to emphasise that the detection of short-lived aerosol events may differ between in situ and remote-sensing (column-integrated) techniques because each method samples different atmospheric layers, and local conditions at the station level may not be representative of the column-averaged aerosol load. This discrepancy was evident on 19 August, where the morning event showed fine particles at the surface level, with eBC concentrations peaking at 12.33 and 13.00 μg m^{-3} in PM_{10} and PM_1 fractions, and SAE reaching 2.19 (Figures 5b and 5c), contrasting with the columnar measurements of FMF and AE (Figures 4a and 4b), which indicated coarser particles with values below 0.4 and 0.5, respectively. The lidar data (Figure 4d) clarify this discrepancy where low δv values at altitudes below 3 km a.s.l. revealed a distinct aerosol layer near the surface for both events on 19 August~~, coinciding with the surface events and indicating~~. The consequence of this pronounced aerosol layering above the station is that surface observations detected the arrival of smoke-dominated air masses~~at ground level. However, this layer was not detected in the~~, whereas column-integrated ~~measurements due to~~ observations indicated the dominance of coarser desert dust particles~~in the upper atmosphere~~.

This local wildfire also had a direct impact on in situ atmospheric concentrations of CO_2, CH_4, and CO at IZO, which showed higher-than-usual values between 17 and 19 August (Figure 6). During the event, CO_2, CH_4, and CO concentrations increased significantly and reached peaks of approximately 520 ppm, 2800 ppb, and 12000 ppb, respectively, well above typical values at IZO (410-430 ppm for CO_2, 1800-2100 ppb for CH_4 and 50-200 ppb for CO). These marked increases (about 25 % for CO_2,

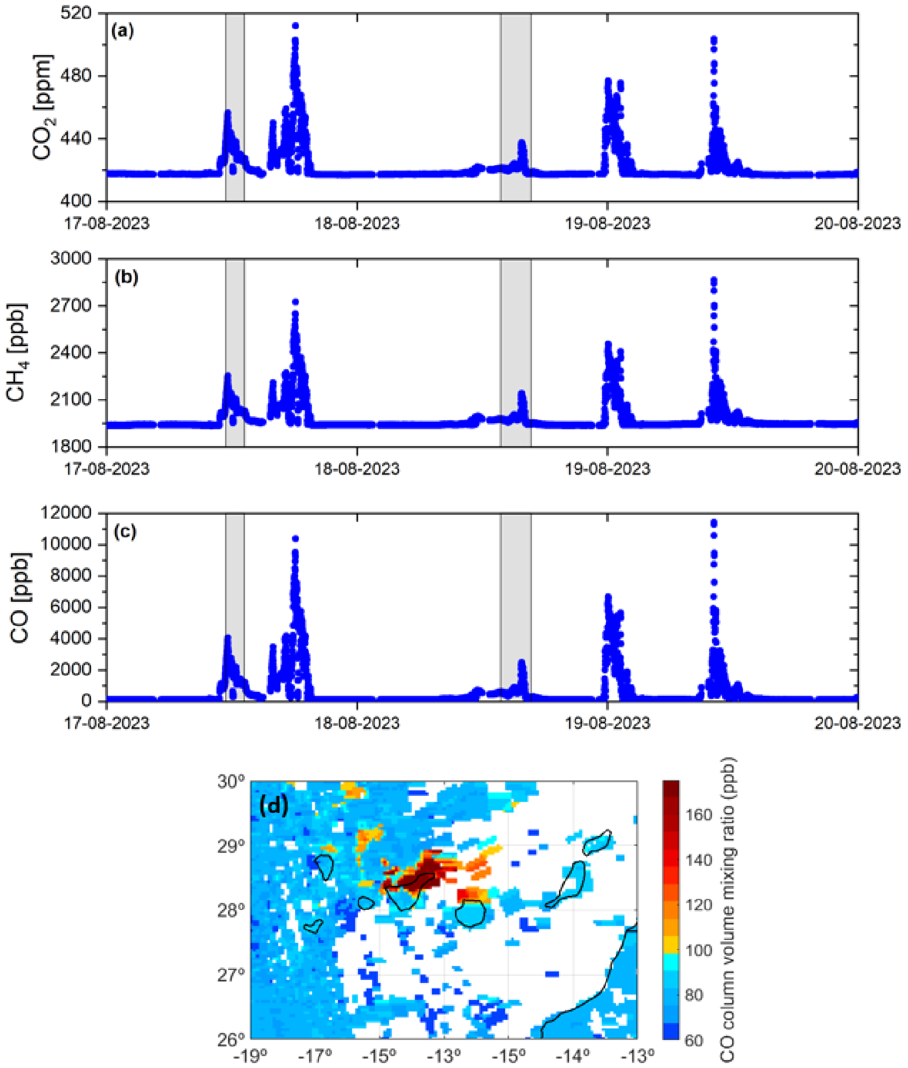

Figure 6. Time series of 1-minute averaged dry-air mole fractions of (a) CO$_2$ (ppm), (b) CH$_4$ (ppb) and (c) CO (ppb) from in situ measurements by the Picarro analyser at the Izaña Observatory between 17 and 19 August 2023. (d) Satellite CO total column from Copernicus Sentinel-5p TROPOMI over the Canary Islands between 17 and 19 August 2023 (using a 3-day moving average).

35 % for CH_4 and nearly two orders of magnitude for CO) are fully consistent with the presence of intense biomass-burning plumes over the observatory during the event, as confirmed by collateral smoke transport identified in Sentinel-5P TROPOMI CO observations (Figure 6d).

The temporal evolution of the in situ measurements reveals a strong correspondence between peaks in particulate matter (PM_{10}, $PM_{2.5}$), eBC, and greenhouse gases (CO_2, CH_4, CO) (Figure 5 and 6). All maxima occurred concurrently with the periods of highest columnar AOD and strongest backscatter in the lidar profiles. This simultaneity provides robust evidence that the observed perturbations in aerosol and gas concentrations originated from the same wildfire plume. These independent datasets confirm the coherent atmospheric signature of fresh biomass-burning emissions, reinforcing the interpretation of a strongly localised and intense smoke influence at Izaña during the 17–19 August events.

4.1.1 ~~Spectral aerosol radiative forcing and efficiency~~

4.2 Spectral aerosol radiative forcing and efficiency

The influence of aerosols on spectral irradiance becomes evident when examining the spectra measured during the two days with the highest AOD (17 and 18 August 2023; Figure 4a). Figure 7 illustrates the pronounced variability observed in the GHI_λ, DNI_λ, and DHI_λ components, highlighting the impact of these high-turbidity episodes, which lead to substantial spectral attenuation and angular redistribution of solar radiation. During the most intense smoke events, daily GHI_λ was reduced by 21–27 %, DNI_λ by 72–99 %, while DHI_λ irradiance increased by 72–75 % compared with clean-sky conditions at IZO. These results are similar to those observed during the 2021 Greece wildfires, with decreases of 10–20 % in daily GHI_λ (Masoom et al., 2023).

These measurements represent one of the few detailed spectral characterisations (300–1100 nm) of extreme biomass-burning aerosol episodes at a high-altitude observatory. The exceptionally large AOD values observed at IZO (up to 3.6 at 500 nm) place this event among the most intense smoke episodes documented.

The spectral radiative effects of biomass-burning aerosols were analysed at the times when the AOD at 500 nm (Figure 4 a, c, Table 1) reached its maximum values on each study day: 11:56 UTC (SZA 22.7°, AOD 3.63) on 17 August and 15:46 UTC (SZA 39.1°, AOD 2.25) on 18 August. Figure 8 shows the spectral distribution of irradiance, radiative forcing (ΔF; W $m^{-2}nm^{-1}$), spectral AOD determined from EKO RSB measurements and radiative forcing efficiency (ΔF^{eff}; W $m^{-2}nm^{-1}AOD^{-1}$). These large AOD values confirm the strong presence of smoke particles over the site, which substantially altered the radiative fluxes and their spectral distribution. Clear differences between the two days, as well as among the various SZA conditions, highlight the temporal evolution of the aerosol optical properties and their influence on surface radiation. The ΔF^{eff} was calculated using Equation 6, based on the spectral AOD retrieved at the EKO RSB wavelengths.

The differences between the two days reflect both the varying aerosol load and the changes in solar geometry, with the higher AOD and smaller SZA on 17 August enhancing the radiative impact. Slight variations in aerosol optical properties, including potential differences in fine-mode dominance or absorption, may also contribute to the observed contrast.

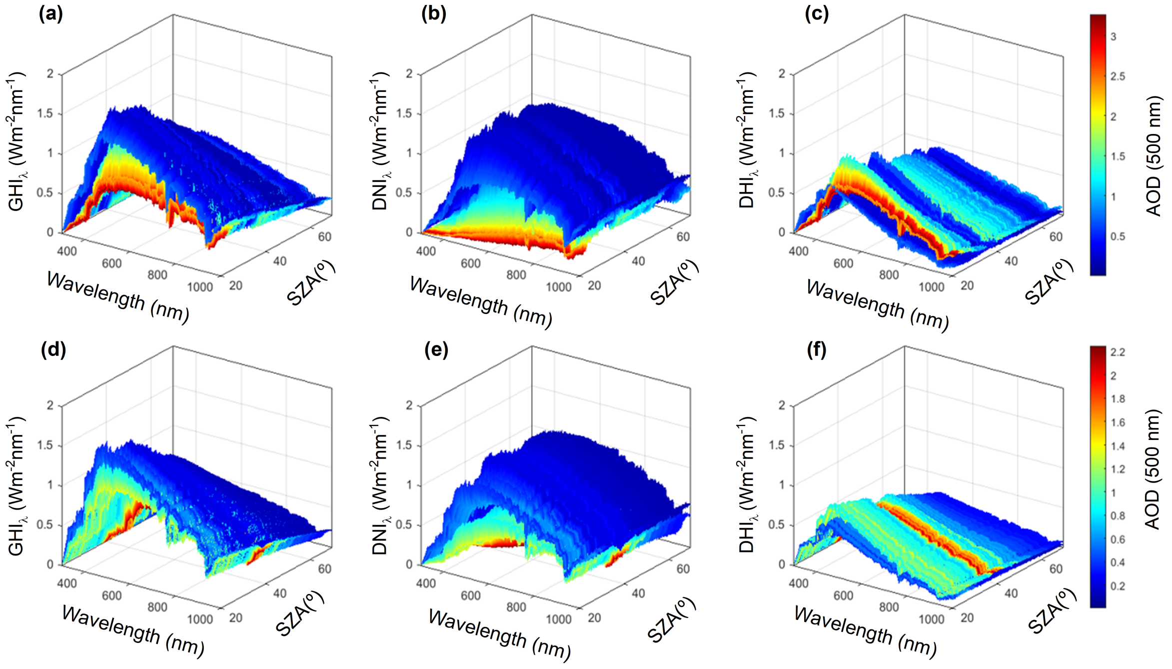

Figure 7. Spectral global-horizontal (GHI_λ), direct-normal (DNI_λ), and diffuse-horizontal (DHI_λ) irradiance measured on 17 August (a, b, c) and 18 August (d, e, f) 2023 between 06:30 and 19:50 UTC (a total of 793 spectra) using the EKO RSB at IZO. The colour bar shows the AOD at 500 nm retrieved from the EKO RSB measurements.

The spectral irradiance of GHI_λ, DNI_λ, and DHI_λ exhibits a clear contrast between the measurements obtained under clean conditions (dashed lines) and those affected by fire events (solid lines) (Figure 8a, e). On both days, the high AOD caused a strong attenuation of DNI_λ irradiance, mainly below 700 nm, accompanied by an enhancement of the DHI_λ component. The stronger impact between 450 and 460 nm, with ΔF values of -1.69 and -1.59 W m^{-2}nm^{-1}, respectively, indicates the dominance of fine-mode smoke particles which scatter efficiently short wavelengths. A pronounced attenuation of the DNI_λ spectral irradiance and enhancement of the DHI_λ component are observed, reflecting the strong scattering capacity of biomass-burning aerosols. This enhanced scattering capacity is consistent with the high SSA values obtained from the surface measurements (Fig. 5 in Sect. 4.1). The resulting spectra of ΔF are negative for the DNI_λ and GHI_λ components and positive for the diffuse one, indicating a net surface cooling effect dominated by scattering processes. The magnitude of the ΔF is larger on 17 August (AOD$_{500nm}$ = 3.63) than on 18 August (AOD$_{500nm}$ = 2.25), consistent with the higher aerosol load and the smaller solar zenith angle. The ΔF^{eff} spectra (Figure 8d, h) exhibit similar shapes for both days, with maximum efficiency in the visible region (400–800 nm), suggesting that the optical properties of the aerosols, likely dominated by biomass-burning particles, remained relatively constant throughout the episode.

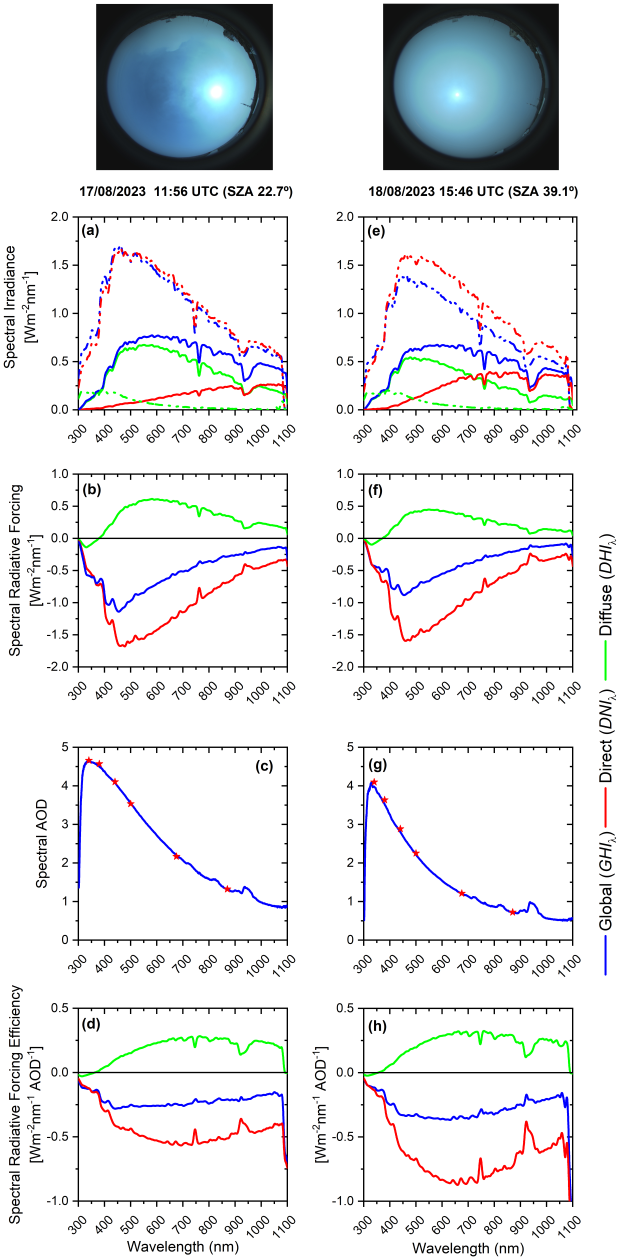

Figure 8. Spectral irradiance (W m^{-2}nm^{-1}) (a, e), spectral radiative forcing (W m^{-2}nm^{-1}) (b, f), spectral AOD obtained from EKO RSB measurements (blue line) and AOD obtained from CIMEL (red stars) (c,g), and spectral radiative forcing efficiency (W m^{-2}nm^{-1}AOD^{-1}) (d, h) for selected times corresponding to the two maximum AOD cases during the biomass-burning aerosol episode at IZO on 17 and 18 August 2023, with AOD$_{500nm}$ values of 3.63 and 2.25, respectively. The panels correspond to measurements at 11:56 UTC (SZA = 22.7°) on 17 August (a-d) and 15:46 UTC (SZA = 39.1°) on 18 August (e-h). The sky-camera images show the corresponding sky conditions at each time. Blue, red, and green lines represent global (GHI_λ) direct-normal (DNI_λ), and diffuse (DHI_λ) irradiance components, respectively. The dashed lines in panels (a, b) represent the spectra measured experimentally under clean conditions (6 August 2023 at 11:50 UTC, SZA = 22.6°, and 15:55 UTC, SZA = 39.1°).

The integrated spectral radiative forcing values (ΔDF and ΔDF^{eff}) determined from Equation 7 are shown in Table 2. The results are consistent with the spectral behaviour discussed in Figure 8. The total ΔDF$^{GHI_\lambda}$ (300–1100 nm) reached -395 W m^{-2} on 17 August and -299 W m^{-2} on 18 August, confirming a strong surface cooling effect during the biomass-burning episode. The forcing was dominated by the DNI_λ component ($\sim$ -700 and -609 W m^{-2}, respectively), while the DHI_λ component partially compensated for this loss with positive values ($\sim$ +250 and +174 W m^{-2}), as expected under intense scattering conditions.

The band-integrated ΔF^{eff} exhibited a distinct spectral dependence, peaking in the visible range (-77 to -99 W m^{-2}AOD^{-1} for the GHI_λ component), consistent with the strong scattering capacity of fine-mode smoke particles. Near-IR efficiencies were slightly lower (-66 to -85 W m^{-2}AOD^{-1}), while UV contributions remained minor ($\sim$ -10 W m^{-2}AOD^{-1}). For the DNI_λ component, ΔF^{eff} reached up to -211 W m^{-2}AOD^{-1}, whereas the DHI_λ component showed positive values ($\sim$ +50–80 W m^{-2}AOD^{-1}), highlighting the enhanced scattering under high aerosol load. Integrated over 300–1100 nm, total ΔF^{eff} reached -154 W m^{-2}AOD^{-1} on 17 August and -194 W m^{-2}AOD^{-1} on 18 August, indicating a slightly higher radiative efficiency on the latter day despite lower AOD. These findings confirm that biomass-burning aerosols at IZO produced a marked shortwave surface cooling dominated by visible-range scattering processes.

Spectrally, for both GHI_λ and DNI_λ spectral radiation, the visible range (400–700 nm) contributed the most to the total forcing ($\sim$60–65 %), followed by the near-IR range ($\sim$22–25 % for GHI_λ and $\sim$28–31 % for DNI_λ) and the UV range ($\sim$13 % for GHI_λ and $\sim$7 % for DNI_λ) for the two days. This distribution matches the maximum in the incident solar irradiance and the high scattering efficiency of fine-mode smoke particles in the visible region. ΔF^{eff} also reflects the larger radiative impact per unit AOD on 18 August, despite the lower aerosol load, suggesting a slightly enhanced absorption or differences in aerosol optical properties and solar geometry. Overall, these integrated values confirm that biomass-burning aerosols at IZO produced a pronounced shortwave radiative cooling dominated by scattering processes, with maximum efficiency in the visible range.

Besides the instantaneous spectral and band-integrated values, daily radiative forcing was also computed to assess the accumulated shortwave impact of the smoke-laden days. On 17 August, the total daily forcing reached -56 (GHI_λ), -162 (DNI_λ), and +70 W m^{-2} (DHI_λ), while on 18 August the corresponding values were -44, -137, and +60 W m^{-2}, respectively. The daily forcing efficiencies were -77, -313, and +138 W m^{-2}AOD^{-1} for the GHI_λ, DNI_λ, and DHI_λ components on 17 August, and -84, -332, and +145 W m^{-2}AOD^{-1} on 18 August. These values are consistent with previously reported daily-scale radiative impacts of biomass-burning aerosols. For example, Zhuravleva et al. (2017) reported global radiative forcing values ranging from -13 to -60 W m^{-2} and efficiencies between -80 and -40 W m^{-2}AOD^{-1} during the 2012 Siberian wildfires.

In addition to the instantaneous spectral and band-integrated forcing values discussed above, the temporal evolution of the broadband shortwave radiative forcing was analysed over the two smoke-affected days in order to evaluate the diurnal behaviour of the aerosol perturbation (Figure 9). The time series shows a clear enhancement in the magnitude of the forcing during periods of strongest smoke influence, with the largest cooling occurring around local noon, when solar irradiance is at its maximum. On 17 August, the forcing exhibits a pronounced peak between approximately 11:30 and 13:30 UTC, coinciding with the period of highest aerosol loading observed at the station. On 18 August, the forcing remains significant over a broader time interval, with a maximum around 15:30 UTC, consistent with the later arrival of the densest smoke plume (Figure 4a).

Table 2. Averages of AOD (mean±std), ΔDF (W m^{-2}) and ΔDF^{eff} (W m^{-2} AOD^{-1}) for GHI_λ, DNI_λ and DHI_λ spectral radiation components in the four spectral ranges (UV: 300–400 nm, VIS: 400–700 nm, near-IR: 700–1100 nm, and Total: 300-1100 nm) for the two study cases (17 August 11:56 UTC (SZA 22.7°) and 18 August 15:46 UTC (SZA 39.1°)).

	AOD	ΔDF^{GHI_λ} ($\Delta DF^{eff-GHI_\lambda}$) Wm^{-2} ($Wm^{-2}AOD^{-1}$)	ΔDF^{DNI_λ} ($\Delta DF^{eff-DNI_\lambda}$) Wm^{-2} ($Wm^{-2}AOD^{-1}$)	ΔDF^{DHI_λ} ($\Delta DF^{eff-DHI_\lambda}$) Wm^{-2} ($Wm^{-2}AOD^{-1}$)
UV: 300–400 nm				
~~17/08/2023~~ 17-08-2023 11:56	4.75±0.06	-52.8 (-11.1)	-51.8 (-10.9)	-5.0 (-1.0)
~~18/08/2023~~ 18-08-2023 15:46	3.98±0.33	-39.0 (-10.1)	-47.1 (-12.4)	-2.5 (-0.5)
VIS: 400–700 nm				
~~17/08/2023~~ 17-08-2023 11:56	3.21±0.76	-246.0 (-76.6)	-429.5 (-139.0)	150.3 (51.7)
~~18/08/2023~~ 18-08-2023 15:46	1.98±0.65	-191.1 (-99.2)	-391.4 (-211.3)	112.7 (64.9)
near-IR: 700–1100 nm				
~~17/08/2023~~ 17-08-2023 11:56	1.42±0.31	-95.4 (-65.7)	-217.7 (-149.8)	105.5 (72.5)
~~18/08/2023~~ 18-08-2023 15:46	0.78±0.16	-68.1 (-84.5)	-169.1 (-210.3)	63.4 (79.0)
Total: 300–1100 nm				
~~17/08/2023~~ 17-08-2023 11:56	2.64±1.30	-394.9 (-153.7)	-699.9 (-300.0)	251.1 (123.2)
~~18/08/2023~~ 18-08-2023 15:46	1.73±1.15	-298.6 (-194.0)	-608.4 (-434.5)	173.8 (143.5)

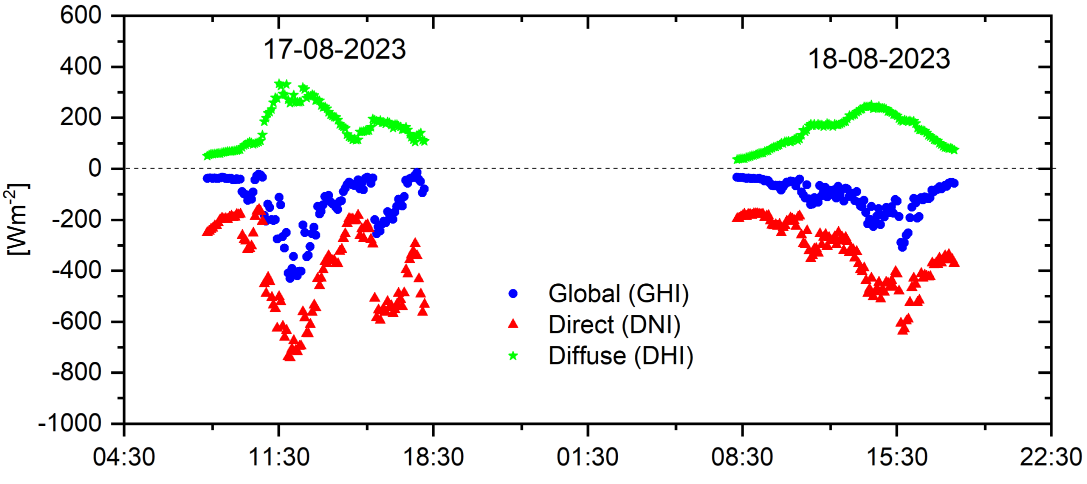

Figure 9. Temporal evolution of the radiative forcing components (blue: global (*GHI*), red: direct (*DNI*) and green: diffuse (*DHI*) radiation) at Izaña Observatory during the wildfire smoke events of 17 and 18 August 2023.

Although the magnitude observed at IZO lies among the highest documented due to the exceptional aerosol load, this comparison reinforces that the radiative response observed at IZO is consistent with the upper bounds of biomass-burning forcing reported in the literature.

5 Conclusions

The extreme wildfire episode affecting Tenerife in August 2023 resulted in an exceptional aerosol perturbation over the Izaña Observatory, characterised by an extraordinarily high aerosol load dominated by fine-mode smoke particles. The event reached AOD_{500nm} (AE) values of 3.63 (1.71) and 2.25 (2.04) on 17 and 18 August 2023, respectively, among the highest ever reported at this high-mountain site, and was accompanied by fine-mode fractions exceeding 0.9, indicating the presence of freshly emitted biomass-burning aerosols. Spectral measurements revealed a strong attenuation of global (GHI_λ) and direct-normal (DNI_λ) irradiance, particularly at wavelengths below 700 nm where fine-mode scattering is most effective, along with a marked enhancement of diffuse irradiance (DHI_λ). As a result, daily global irradiance decreased by 21–27 %, while direct-normal irradiance nearly collapsed (-72 to -99 %), demonstrating the episode's strong radiative impact.

The radiative forcing analysis showed that scattering by fine-mode smoke dominated the shortwave response, with spectral forcing strongly negative for direct and global irradiance but positive for the diffuse component. Maximum forcing occurred in the visible region, consistent with the optical properties of freshly emitted smoke. On 17 and 18 August, shortwave integrated radiative forcing reached -395 and -299 W m^{-2}, respectively, confirming a strong surface cooling effect during the biomass-burning episode. On 17 August, total daily forcing amounted to -56 W m^{-2} (GHI_λ), -162 W m^{-2} (DNI_λ), and +70 W m^{-2} (DHIλ), while on 18 August the corresponding values were -44, -137, and +60 W m^{-2}, respectively. The daily forcing efficiencies were -77, -313, and +138 W $\mathrm{m}^{-2}\mathrm{AOD}^{-1}$ for the GHI_λ, DNI_λ, and DHI_λ components on 17 August, and -84, -332, and +145 W $\mathrm{m}^{-2}\mathrm{AOD}^{-1}$ on 18 August. These values are consistent with those reported by Zhuravleva et al. (2017) during the 2012 Siberian wildfires.

Complementary multi-platform observations reinforce this interpretation. Coincident increases in PM_{10}, $\mathrm{PM}_{2.5}$, eBC, and combustion-related greenhouse gases (CO_2, CH_4, CO) demonstrate the direct influence of the wildfire plume on the atmospheric composition at IZO, providing a comprehensive picture of the physical and chemical signatures associated with an intense near-source smoke intrusion.

From a climate perspective, the magnitude and spectral signature of the radiative perturbations documented here highlight the importance of improving the representation of fine-mode smoke aerosols in radiative transfer models and Earth-system simulations. Current models can face difficulties in reproducing the optical complexity and high scattering efficiency of fresh biomass-burning aerosols, particularly when they are transported into the free troposphere through fire-induced vertical motion. As the frequency, intensity, and injection height of wildfire emissions are expected to evolve under future climate conditions, incorporating observationally informed parametrisations will help refine estimates of surface energy budgets, cloud–aerosol interactions, and regional climate responses. The extreme Tenerife episode therefore provides a useful reference case for model evaluation and illustrates the value of coordinated observations for improving our understanding of wildfire–climate interactions.

Data availability. The EKO RSB data used in this study are available on request from the Izaña WMO-MLC. The AERONET data are freely available from the NASA Goddard Space Flight Center (https://aeronet.gsfc.nasa.gov; last access 4 December 2025). Data from MPLNET used in the present study can be obtained from https://mplnet.gsfc.nasa.gov/ (last access: 21 October, 2025). In situ surface data from the Izaña Atmospheric Observatory contribute to the WMO GAW program and are available from the World Data Centre for Greenhouse Gases (WDCGG, https://gaw.kishou.go.jp/policy/gaw/, last access: 26 October 2025). TROPOMI data (Copernicus Sentinel-5P) are publicly available from the Sentinel-5P data hub at https://maps.s5p-pal.com/co/ (last access: 3 December 2025). TSI nephelometer scattering coefficients and PM_{10} MAAP equivalent black carbon data are publicly available through the EBAS database (https://ebas.nilu.no), the World Data Centre for Aerosols (WDAC) hosted by NILU. TEOM mass concentration data, and PM_1 MAAP equivalent black carbon data are available upon request to the authors.

Author contributions. All co-authors contributed to the preparation and writing of the manuscript. RDG, AB, and PGS designed the structure and methodology of the paper, discussed the results, and participated in the retrieval analysis. RDG wrote the main part of the paper and performed the required calculations. VC provided valuable ideas used in this study and guidance based on her experience in spectroradiometry and photometry. AB, PGS, YG, OA, and FA wrote Sections 2.3 and 4.1 related to remote sensing and in situ aerosol measurements. AAH, SLL, and PPR wrote Sections 2.3 and 4.1 related to greenhouse gases. JJB provided the meteorological data and its interpretation. RR performed the maintenance and daily checks of the EKO RSB spectroradiometer.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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