Emerging extreme Saharan-dust events expand northward over the Atlantic and Europe prompting record-breaking PM$_{10}$ and PM$_{2.5}$ episodes

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Abstract. Unprecedented extreme Saharan-dust (duxt) events have recently expanded northward, from subtropical NW Africa to the NE Atlantic and SW Europe, affecting the Canary Islands and mainland Spain. These six historic duxt episodes occurred 3-5 February 2020, 22-29 February 2020, 15-21 February 2021, 14-17 January 2022, 29 January - 1 February 2022 and 14–20 March 2022. We analysed data of 330 Governmental Air Quality Monitoring Stations (AQMSs) of Spain, where PM$_{10}$ and PM$_{2.5}$ are measured with European EN-standards, and found that during duxt events PM$_{10}$ concentrations are underestimated due to technical limitations of some PM$_{10}$ monitors to properly measure extremely high concentrations. We assessed the consistency of PM$_{10}$ and PM$_{2.5}$ data and reconstructed 1414 PM$_{10}$ (1h average) data of 48 AQMSs by using our novel duxt-r method. During duxt events, 1-hour average PM$_{10}$ and PM$_{2.5}$ concentrations were within the range 1000-6000 µg/m$^3$ and 400-1200 µg/m$^3$, respectively. The meteorological and dust modelling-reanalyses show that the intense winds leading to massive dust plumes occurred within meteorological dipoles formed by a blocking anticyclone over western Europe and a cut-off low located at the southwest, near the Canary Islands, Cape Verde or into the Sahara. These cyclones reached this region by two main paths: deviated southward from the Atlantic mid-latitudes westerly circulation by the blocking anticyclone over western Europe or deviated northward from the tropical belt. The 22-29 February 2020 event led to (24h average) PM$_{10}$ and PM$_{2.5}$ within the range 600-1840 µg/m$^3$ and 200-404 µg/m$^3$, being the most intense dust episodes ever recorded in the Canary Islands. The 14–20 March 2022 event led to (24h average) PM$_{10}$ and PM$_{2.5}$ values within the range 500-3070 µg/m$^3$ and 100-690 µg/m$^3$ in south-eastern, 200-1000 µg/m$^3$ and 60-260 µg/m$^3$ in central and 150-500 µg/m$^3$ and 75-130 µg/m$^3$ in northern regions of mainland Spain and to 150-430 µg/m$^3$ and 30-80 µg/m$^3$ in the Canary Islands, respectively, being the most intense dust episode ever recorded in mainland Spain. The analysis of the 2000-2022 PM$_{10}$ and PM$_{2.5}$ time series shows that these six duxt events have no precedent in Spain. All duxt events occurred during northern-hemisphere meteorological anomalies characterised by shifted to higher latitudes subtropical anticyclones, anomalous low pressures expanding beyond the tropical belt and a mid-latitudes amplified Rossby-waves undulation; these overall features resemble the anomalies of the atmospheric circulation linked to the anthropogenic global warming.
1 Introduction

Airborne dust aerosol particles are a key component of the Earth System influencing on climate (Kok et al., 2023), ecosystems (Yu et al., 2015), fisheries (Rodríguez et al., 2023) and human health (Domínguez-Rodríguez et al., 2021; Tong et al., 2023). Major dust sources are located in North Africa, the Middle East and inner Asia (Prospero et al., 2002), accounting for 75% of global emissions; secondary sources are located in northern and southern America, southern Africa, Australia and at high latitudes (Kok et al., 2023). Because these sources are located in arid regions they have usually been considered as “natural dust-sources” (e.g. the bed of naturally dried ancient lakes (Ginoux et al., 2012; Prospero et al., 2002)); however a growing body of evidences is showing that human actions such as the soil disruption by traditional grazing and agriculture (Katra, 2020; Mulitza et al., 2010; Vukovic et al., 2021), mining (Rodriguez et al., 2011; Zafra-Pérez et al., 2023), drying of water courses and lakes (Ginoux et al., 2012; Govarchin-Ghale et al., 2021), the expansion of intensive agriculture (Lambert et al., 2020) and wildfires (Yu and Ginoux, 2022) contribute to increase dust emissions.

Dust storms cause huge socio-economic impacts linked to looses of visibility, road traffic disruption and accidents, deviation of air travel or closure of maritime and air navigation space, cardiovascular and respiratory diseases, loose of soil and a decrease in solar energy production (Cañadillas-Ramallo et al., 2022; Domínguez-Rodríguez et al., 2021; Middleton et al., 2021; Miri and Middleton, 2022; Pi et al., 2020). For this reason, a set of operational “dust services” are available to forecast and monitor dust activity by modelling and satellite observations (Mona et al., 2023). In-situ concentrations of PM$_{10}$ and PM$_{2.5}$ (respirable particulate matter -PM- smaller than 10 and 2.5 microns, respectively) regularly measured in air quality monitoring networks are commonly used to assess dust impacts and to validate dust models (Mona et al., 2023). In southern Europe, Saharan dust events tend to increase PM$_{10}$ concentrations up to typical values within the range 40-90 µg/m$^3$ (24h average values), being dust events with (24h average) PM$_{10}>100$ µg/m$^3$ unusual (Millán-Martínez et al., 2021; Pey et al., 2013).

Understanding how climate change is affecting dust emissions is a challenge as these emissions are also affected by the natural atmospheric variability (as traced by ENSO, NAO, AMO and other climatic indexes (Evan et al., 2016)), as well as by the changes in atmospheric circulation and soil properties (e.g. humidity and biological crust (Rodriguez-Caballero et al., 2022)) as the atmosphere warms due to the increasing concentrations of greenhouse gases.

Current climate models are unable to reproduce the historical increase in atmospheric dust loads observed in paleorecords (Kutuzov et al., 2019; Preunkert et al., 2019). Based on models constraining dust emissions, it has been estimated that the global dust mass load in the modern climate is $\approx 56\%$ higher than in pre-industrial times (Kok et al., 2023), with a maximum dust load in the mid-1980s and a subsequent decrease attributed to a decrease in North African and Asian dust emissions linked to a slowdown of the atmospheric circulation interconnected to global warming (Evan et al., 2016; Liu et al., 2020; Ridley et al., 2014). In this scenario of decreasing dust trend in North Africa and Asia, a series of unexpected extreme dust-events have recently occurred.
In March 2018 a “record-breaking Saharan dust plume” crossed the Eastern Mediterranean (Kaskaoutis et al., 2019), leading to PM\textsubscript{10} values of up to (1h-average) 6000 µg/m\textsuperscript{3} (Solomos et al., 2018), a three-fold increase in hospital admissions (Lorentzou et al., 2019; Monteiro et al., 2022) and an accelerated snow melting in the Caucasus (Dumont et al., 2020). In June 2020 the so-called “Godzilla record-breaking trans-Atlantic African dust plume” (Bi et al., 2023; Francis et al., 2020, 2022; Pu and Jin, 2021) led to (24h average) values PM\textsubscript{10} = 453 µg/m\textsuperscript{3} in the Caribbean and PM\textsubscript{10} and PM\textsubscript{2.5} values = 135 and 74 µg/m\textsuperscript{3} in southern United States (Yu et al., 2021), respectively. In March 2021, “record-breaking dust events” in China (Gui et al., 2022) led to (1h-average) PM\textsubscript{10} and PM\textsubscript{2.5} values of up to 7525 µg/m\textsuperscript{3} and 685 µg/m\textsuperscript{3}, respectively (Filonchyk and Peterson, 2022; Zhang et al., 2023). In November 2021, an “extreme dust storm” in Uzbekistan led to (1h average) PM\textsubscript{10} and PM\textsubscript{2.5} concentrations of up to 4575 µg/m\textsuperscript{3} and 705 µg/m\textsuperscript{3} (Nishonov et al., 2023; Xi et al., 2023).

In this study we present a set of unprecedented extreme dust-events that have recently (2020-2022) expanded northward, from North Africa, to the Atlantic and Europe prompting record-breaking PM\textsubscript{10} and PM\textsubscript{2.5} episodes in Spain. The increase in dust activity in this region has recently been studied based on aerosol optical depth - satellite measurements (Cuevas et al., 2023). We also focused on the analysis of the consistency of PM\textsubscript{10} and PM\textsubscript{2.5} data in the Governmental Air Quality Monitoring Networks during the extreme dust events due to the importance of having suitable data in the public databases used for health effects studies, model validation and constrains etc… (Mona et al., 2023). Understanding these emerging extreme dust events is crucial for this region, since climate projections forecast the expansion of the North African drylands toward the northwest, increasing the risk of desertification of Spain and Portugal as the subtropical anticyclone expands in a warming climate (Cresswell-Clay et al., 2022; Guioit and Cramer, 2016).

2 Methodology

2.1 Data of PM\textsubscript{10} and PM\textsubscript{2.5}

We analysed the 2000-2022 data of PM\textsubscript{10} and PM\textsubscript{2.5} recorded in 330 stations of the Governmental Air Quality Monitoring Network of Spain distributed across the 12 Autonomous Regions of Spain and the Autonomous Spanish city of Ceuta. These stations are integrated in the European Air Quality Monitoring Network, which is the largest European infrastructure for PM\textsubscript{10} and PM\textsubscript{2.5} monitoring following standardized methods for measurements, quality assurance (QA) and quality control (QC) (EN-16450:2017 and EN-12341:2015). In these stations, high temporal (10 to 60 minutes) resolution PM\textsubscript{10} and PM\textsubscript{2.5} data are obtained using automatic monitors based on different principle of measurement, such as beta attenuation, tapered element oscillating microbalance and optical particle sizers (Rodríguez et al., 2012), with technical specifications accomplishing the EN-16450:2017 standard. Data of 24h average PM\textsubscript{10} and PM\textsubscript{2.5} are also obtained with the gravimetric reference method (EN-12341:2015), used for QA/QC assessments and for converting the PM\textsubscript{10} and PM\textsubscript{2.5} data obtained with the automatic devices to gravimetric equivalent data by using the European reference protocols (EN-16450:2017). The PM\textsubscript{10} and PM\textsubscript{2.5} data that we
used were provided by the Ministry of Ecological Transition and Demographic Challenge of Spain and by the air quality departments of the Autonomous Regions.

2.2 Complementary modelling and satellite data

We also used data of the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) meteorological reanalysis (Kalnay et al., 1996), of the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) model dust reanalysis (Gelaro et al., 2017) and of satellite Visible Infrared Imaging Radiometer Suite (VIIRS) sensor aboard the Suomi polar satellite.

3 Results and discussion

The set of extreme dust events, to which we will refer with the acronyms dxxt or dx episodes, occurred on 3-5 February 2020 (dx-01), 22-29 February 2020 (dx-02), 15-21 February 2021 (dx-03), 14-17 January 2022 (dx-04), 29 January - 1 February 2022 (dx-05), and 14–20 March 2022 (dx-06). These dust events were characterised by dark and reddish “apocalyptic” skies (Fig.1A-1C). National Spanish and international media (Fig.1), the European Copernicus (Fig.1D) and NASA - Earth Observatory (Fig.1E) platforms reported on these historic events and their impacts on socio economical activities. During the impact of the dxxt-02 event in the Canary Islands, record-breaking temperatures occurred, wildfires were favoured by the windy and dry conditions, solar production energy dropped by a 70%, maritime and air navigation space was closed, and thousands of flights were cancelled with huge economic implications due to the transfer of tourists between the Canary Islands and Europe (Fig.1)(Cuevas et al., 2021).
Figure 1. News on the extreme dust events impacting mainland Spain and the Canary Islands published in international and Spanish national media. Picture of the Cabo de Gata in south-eastern mainland Spain (Almería province) the 15 of March 2022 (dx-06) (taken and provided by Eva de Mas Castroverde).
Figure 1 (continue). Pictures of Tenerife (Canary Islands) the 23 of February 2020 (dx-02) and 30 of January 2022 (dx-05) (taken by the authors). Composite of the websites of Copernicus (https://atmosphere.copernicus.eu/historical-saharan-dust-episode-western-europe-cams-predictions-accurate) and Earth Observatory (https://earthobservatory.nasa.gov/images/149588/an-atmospheric-river-of-dust) reporting on the historic dust event the 15th of March 2022.
3.1 Assessment and reconstruction of PMx data during the duxt events

We analysed the data of PM$_{10}$ and PM$_{2.5}$ (PM$_x$) of 330 Air Quality Monitoring Stations (AQMS) of the 12 Autonomous Regions of Spain and the Spanish Autonomous City of Ceuta. We found that during the duxt events, the ½ hour and 1 hour resolution data of PM$_{10}$ increased up to reach a rather constant ‘saturation’ value, that in most of cases was somewhat lower than 1000 µg/m$^3$ (in many cases between 900 and 1000 µg/m$^3$), no values above this threshold appear in the data records. In these cases, PM$_{10}$ concentrations remained constant during the period of extremely high dust concentrations (typically 5 to 30 hours), a behaviour that was not observed in PM$_{2.5}$, which exhibited a regular variability (with values < 1000 µg/m$^3$) and even increases in the periods when PM$_{10}$ remained (un-)consistently constant. This behaviour can be observed in the time series of PM$_{10}$ (Fig.2A1-A3) and PM$_{2.5}$ (Fig.2B1-B3) linked to the dx01, dx02, dx04, dx05 and dx06 events (dx03 is not included in Fig.2 for the sake of brevity). This saturation threshold close to ≈1000 µg/m$^3$ is the upper operation limit of some PM$_{10}$ monitors and is also the top value of the validation data flag in some data recording commercial software used in many governmental air quality monitoring networks, which assume that PM$_{10}$ concentrations above this threshold may suffer underestimation due to the high load of particles (e.g. accumulated in the filter-tape of the beta instrument or particle coincidence problems in the optical particle sizers leading to a loose of sensitivity) and consequently do not record values above this threshold. In some AQMSs the saturation threshold was found at 500 µg/m$^3$ and even at 200 µg/m$^3$. In fact, the EN-16450:2017 / 12341 /14907 certifications for PM$_{10}$ and/or PM$_{2.5}$ monitors available in the European market are obtained for specific ranges, whose most frequent upper limit is 1000 µg/m$^3$ for many monitors (e.g. Met One™ BAM-1020, Comde Derenda™ APM 2 and Thermo Fisher Scientific™ 5014i, 5030i SHARP, TEOM 1405-F and 1405-DF), although is as low as 200 µg/m$^3$ for some equipment’s (FAIT™ Swam 5a) and as high as 10000 µg/m$^3$ for other devices (e.g. PALAST™ Fidas 200 and 200E) according to the certifications agencies (e.g. TÜV, see https://www.qal1.de/). In all these cases of PM$_{10}$ data affected by saturation, we reconstructed the PM$_{10}$ concentrations with the method described in Fig. 3, which we have called *duxt-r “PM$_{x}$ evaluation and reconstruction method based on ratios during extreme dust events”*. In this duxt-r method: 1) we first identified the invalid 1 hour (or ½ hour or 10 minutes time resolution) PM$_{10}$ data affected by saturation and the associated invalid PM$_{2.5}$/PM$_{10}$ ratios, highlighted with red circles in the example of the dx-04 event shown in Fig. 3A and 3B, 2) then, the PM$_{2.5}$/PM$_{10}$ ratio during the PM$_{10}$ saturation period was estimated by interpolation between the last valid PM$_{2.5}$/PM$_{10}$ data before saturation and the first valid PM$_{2.5}$/PM$_{10}$ after saturation [R$_{2.5/10}(i)$], highlighted with green points in Fig. 3B, 3) finally, the 1 hour (or ½ hour or 10 minutes) resolution PM$_{10}$ concentrations were determined with equation-01.

\[
PM_{10} = \frac{PM_{2.5}}{R_{2.5/10}(i)}
\]  
(1)
We found that the PM$_{2.5}$/PM$_{10}$ ratio during the duxt events were within the range 0.16 to 0.22 in most of AQMSs, a value lower than that observed during regular dust events (typically ≈0.3) and much lower than that observed in environments affected by secondary particle formation and by vehicle exhaust and other combustion emissions (typically within 0.6-0.9) (Rodríguez and López-Darias, 2021).

![Diagram](https://doi.org/10.5194/egusphere-2023-3083)

Figure 2. Time series of 1h average PM$_{10}$ (raw) (A1-A3) and PM$_{2.5}$ (B1-B) and evaluated and reconstructed PM$_{10}$ data (C1-C3) during February 2020, January 2022 and March 2022, indicating the duxt events. The number of AQMSs included in each plot is shown. PM$_{10}$ (raw) means original raw (non-reconstructed) data (A1-A3). Data of PM$_{2.5}$ are also raw (B1-B3). PM$_{10}$ data of plots C1-C3 combines measured valid and reconstructed data.
Figure 3. Evaluation, reconstruction and validation of data with the duxt-r method. Plots (A–C) shows data of El Charco site (Fuerteventura) during dx-04 event (14-17 January 2022): (A) data of PM$_{10}$ (raw, i.e. including saturated values) and PM$_{2.5}$, (B) the measured PM$_{2.5}$/PM$_{10}$ (raw) ratio and the interpolated PM$_{2.5}$/PM$_{10}$ ratio $[R_{2.5/10}(i)]$, and (C) PM$_{2.5}$, PM$_{10}$ (raw) and PM$_{10}$ reconstructed data. Invalid data due to PM$_{10}$ underestimation are highlighted with red circle (A and B) and red points (C and D). D1–D4) scatterplot of PM$_{2.5}$ and PM$_{10}$ data highlighting valid data (black circle), invalid PM$_{10}$ data (red circle) and reconstructed PM$_{10}$ data (green circle). E1–E4) reconstructed versus measured PM$_{10}$ data.
In our database, we replaced the PM$_{10}$ saturated data by the new PM$_{10}$ re-constructed data, i.e. the red (saturated) points shown in Fig. 3C were replaced by the green re-constructed points. At each site (AQMS), the consistency of the reconstructed data was assessed by analysing the scatter plot of the PM$_{2.5}$ versus PM$_{10}$ data (Fig. 3D1-3D4). As example, the results obtained in AQMSs located in Almería province (Mediterraneo AQMS) and Murcia (Mompean AQMS) in south-eastern Spain, Salamanca province (Salamanca-6 AQMS) in central northern Spain, and in Fuerteventura (Canary Islands) (Fig. 3D1-3D4) is shown (Fig.3D1-3D4). With this method, the red PM$_{10}$-saturated data shown in Fig. 3D1-3D4 were replaced by the green (reconstructed) data.

Because of the technical manufacturing specification the automatic PM$_{10}$ and PM$_{2.5}$ monitors of four AQMSs were able to record valid and consistent PM$_{10}$ and PM$_{2.5}$ data higher than 1000 $\mu$g/m$^3$. We used these records to validate this methodology (Fig.3E1, 3E2 and 3E4). At these sites, we re-constructed the PM$_{10}$ concentrations above 1000 $\mu$g/m$^3$ as if they had experienced saturation and then we compared the “reconstructed versus the measured PM$_{10}$ concentrations”; for this comparison we also included data between 500 and 1000 $\mu$g/m$^3$ for the purpose of having a larger dataset (i.e. all PM$_{10}$ data $>$ 500 $\mu$g/m$^3$). We found that the difference between re-constructed and measured PM$_{10}$ concentrations ranged between 2 and 9% (Fig.3E1-3E4).

In other few AQMSs using beta attenuation devices able to provide PM$_{10}$ $>$ 1000 $\mu$g/m$^3$, we found a low PM$_{10}$ variability above this threshold (indicating looses of sensitivity due to mass overload in the filter tape) that was inconsistent with the variability in PM$_{2.5}$ and that resulted in PM$_{2.5}$/PM$_{10}$ ratios similar to those affected by the saturation as described above (red circles in Fig.3A); at these sites we also reconstructed the PM$_{10}$ with the duxt-r method (Fig.3). Finally, the PM$_{10}$ data measured with the automatic monitors (measured + reconstructed) were converted to gravimetric equivalent data by intercomparison with PM$_{10}$ data obtained with the gravimetric reference method (EN 12341:2015; 24h sampling, available during 7 to 25 days/month depending on the AQMS) using the standardised procedure (EN-16450:2017).

The new dataset obtained with this duxt-r method (PM$_{10}$ measured + reconstructed and then converted to gravimetric equivalent) evidences that 1-hour average PM$_{10}$ data that appeared as “saturated” at 1000 $\mu$g/m$^3$ actually reached values close to 6000 $\mu$g/m$^3$ in the dx-02 event, close to 2000 $\mu$g/m$^3$ in the events dx-01, dx-04 and dx-05, and between 3000 and 4500 $\mu$g/m$^3$ in the events dx-06 (Fig.2C1-2C3).

By applying this methodology, we reconstructed a total of 1414 hourly PM$_{10}$ data of 48 AQMSs belonging to the regions of Canary Islands (39), Andalucía (5), Murcia (1) and Castilla y León (2) and Madrid (2). The data we reconstructed with this method are already available in public data bases of the Governmental Air Quality Networks of Spain, the Ministry of Ecological Transition and the European Environment Agency. The PM$_{10}$ data of other 44 AQMSs that also experienced PM$_{10}$ saturation could not be reconstructed due to the lack of simultaneous PM$_{2.5}$ measurements, a total of 655 hourly data in these AQMSs located in the Canary Islands (14), Andalucía (10), Extremadura (2), Castilla y León (11) and Murcia (7). Just to
illustrate the huge importance of re-constructing the data, a brief comparison (for a few AQMS) of the 24h average PM$_{10}$ concentrations calculated with saturated PM$_{10}$ data vs reconstructed PM$_{10}$ data: (1) 948 vs 3069 µg/m$^3$ 15 March 2022 in Almeria province (Mediterraneo AQMS), (2) 740 vs 1840 µg/m$^3$ 23 Feb 2020 in Gran Canaria (Playa del Inglés AQMS), (3) 1238 vs 1684 µg/m$^3$ 23 February 2020 in Tenerife (Tomé Cano AQMS, affected by filter mass overload), (4) 577 vs 1421 µg/m$^3$ 23 February 2020 in Tenerife (Piscina Municipal AQMS), (5) 527 vs 621 µg/m$^3$ 15 March 2022 in Granada province (Palacio de Congresos AQMS).

3.2 The extreme dust events

The six dust events occurred between February 2020 and March 2022. Four of these episodes affected both the Canary Islands (off NW Africa) and mainland Spain (SW Europe), whereas two of them only affected to the Canaries.

The first two events occurred in February 2020 (Fig.4): 3-5 Feb 2020 (dx-01; Fig.4A1) and 22-29 Feb 2020 (dx-02; Fig.4A2). Throughout six weeks (from mid-January to ending February) a blocking anticyclone established over Iberia, i.e. the Iberian Peninsula (Fig. 4E and 4G), resulting in anomalous easterly wind over central Algeria (wind anomaly not shown for the sake of brevity), a scenario favourable to dust events (Alonso-Pérez et al., 2011a). On 3-5 Feb 2020 a cyclone reached Cape Verde, the low (over Cabo Verde) to high (over Iberia) L-to-H dipole configuration (Fig.4E) resulted in a strong pressure/geopotential gradient and winds that prompted dust emissions and a dense plume of Saharan dust that expanded over the Atlantic to the Canary Islands and the Azores (Fig.4F). Across the Canary Islands the dx-01 event resulted in (i) 1h average PM$_{10}$ and PM$_{2.5}$ concentrations within the range 500-2100 µg/m$^3$ (Fig.2C1) and 100-560 µg/m$^3$ (Fig.2B1), respectively, and (ii) 24h average PM$_{10}$ and PM$_{2.5}$ concentrations within the range 200-535$^\circ$ µg/m$^3$ (Fig.4A1; Fig.5A1; $^\circ$ maximum at Tenerife, San Miguel Tajao AQMS) and 400-1129$^\circ$ µg/m$^3$ (Fig.4A2; Fig.5A2) ($^\circ$Tenerife, Tomé Cano AQMS), respectively. Dust events prompted by the summer North African dipole (NAFDI) was originally introduced by Rodríguez et al. (2015). This concept of meteorological L-to-H dipoles has also been found to drive dust events in the Middle East (Kaskaoutis et al., 2015, 2017) and in the June 2020 Godzilla dust event (Francis et al., 2020).

On 22 Feb 2020, a new cyclone reached again the region of Cape Verde, resulting in a similar L-to-H dipole meteorology (Fig.4G) which prompted a dusty jet stream over the Canary Islands (Fig.4A2, 4H and 4I) and the subtropical North Atlantic. This scenario caused the dark oranges skies, record breaking temperatures, wildfires linked to strong dry winds, closure of maritime and air navigation space and the massive (thousands) flight cancellations described above (Fig.1)(Cuevas et al., 2021). During this dx-02 event, extreme PM$_{x}$ concentrations were recorded in the Canary Islands, with: (i) 1h average PM$_{10}$ and PM$_{2.5}$ concentrations within the range 2000-5254$^\circ$ µg/m$^3$ (Fig.2C1) ($^\circ$Gran Canaria, Arinaga AQMS) and 400-1129$^\circ$ µg/m$^3$ ($^\circ$Gran Canaria, Mercado Central AQMS) (Fig.2B1), respectively, and (ii) 24h average PM$_{10}$ and PM$_{2.5}$ concentrations...
within the range $600-1840\,\mu g/m^3$ (Fig.4B1, 5B1) (='Gran Canaria, Playa del Inglés AQMS) and $200-404\,\mu g/m^3$ (Fig.4B2, 5B2) (=Gran Canaria, Playa del Inglés AQMS), respectively. Concentrations (24h average) of PM$_{10}$ during this dx-02 event were up to 6 times higher than the upper limit of PM$_{10}$ during the regular dust events in the Canary Islands ($\approx 300\,\mu g/m^3$) and also much higher than the extraordinary $680\,\mu g/m^3$ recorded during the dust event of 26 January 2000 (Viana et al., 2002). During this dx-02 episode, the highest (24-h average) PM$_{10}$ ($1200-1840\,\mu g/m^3$) and PM$_{2.5}$ ($230-404\,\mu g/m^3$) concentrations were recorded in the AQMSs located in the central part of the dust plume (Fig.5B1-5B2). After 24 Feb 2020 the Saharan dust plume shifted northward over the Atlantic reaching northern Spain (Fig.4J), resulting in (24h average) PM$_{10}$ and PM$_{2.5}$ concentrations within the range $70-155\,\mu g/m^3$ (Fig.4C1) and $20-33\,\mu g/m^3$ (Fig.4C2) in central Spain (Madrid, Extremadura and Castilla La Mancha regions) and (24h average) PM$_{10}$ concentrations within the range $80-200\,\mu g/m^3$ in eastern Spain (Comunidad Valenciana region) (Fig.4D), respectively. The re-analysis of MERRA-2 properly tracked these two dx-01 & dx-02 events, with dust and dust$_{2.5}$ (i.e. dust in the PM$_{2.5}$ fraction) within the range of the PM$_{10}$ and PM$_{2.5}$ concentrations recorded in the AQMS (see orange circles in Figure 4B-4D).

The third dust event (dx-03: 15-21 Feb 2021) (Fig.6D) was also caused by the intense wind (Fig.6C) linked a dipole L-to-H meteorology (Fig.6B), with the associated blocking anticyclone located over Iberia and a cyclone over the Sahel (Fig.6B). The impact on the Canary Islands occurred during 15-19 Feb 2021 (Fig.6C); the 16 Feb 2021 resulted in 24h average PM$_{10}$ and PM$_{2.5}$ concentrations within the range $400-638\,\mu g/m^3$ (Fig.6A1)(='Las Galletas AQMS, Tenerife) and $80-205\,\mu g/m^3$ (Fig.6A2)(='Las Galanas, La Gomera), respectively. On 16 Feb 2021, the highest PM$_{10}$ (> $480\mu g/m^3$) and PM$_{2.5}$ (> $120\mu g/m^3$) concentrations were recorded on the western side of the Canary Islands (Fig. 5C1-5C2). Subsequently, the dusty air mass tracked the northward anticyclonic circulation, reaching mainland Spain (18-21 Feb 2021; Fig.6E) and resulting in 24h average PM$_{10}$ and PM$_{2.5}$ concentrations within the range $75-150\,\mu g/m^3$ (Fig.6A3) and $20-55\,\mu g/m^3$ (Fig.6A4) in Madrid region, respectively. The MERRA-2 reanalysis properly tracked the dx-03 event, except during the 21 of Feb, when it clearly over estimated dust concentrations in central mainland Spain (see orange circles in Figure 6A1-6A4). A few days later, 23-28 Feb 2021, another dust event impacted across central to northern and eastern Europe due to eastward shift the L-to-H dipole and the resulting northward dust transport across the central Mediterranean (Meinander et al., 2023; Peshev et al., 2023).
Figure 4. Events dx-01 and dx-02. Satellite view (NOAA-20 VIIRS) of the dust plume during the first day of dx-01 (A1) and dx-02 (A2) events. Time series of 24h average PM$_{10}$ and PM$_{2.5}$ data recorded in AQMSs of the Canary Islands (B1-B2), central Spain (C1-C2) and eastern Spain (D), which includes dust and dust$_{2.5}$ concentrations ($\mu$g/m$^3$) obtained with MERRA-2 model (orange circle) in each region (27-29°N, 15-17.5°W domain for the Canary Islands, 39-41°N, 6.8-4.3°W for central Spain and 37-41.5°N, 6.8°W-1.2°E for eastern Spain). The geopotential height (GPH) of the 850hPa is shown for the first day of dx-01 (E) and dx-02 (G) events. Wind vector at 850hPa for the 23 Feb 2020 dx-02 (E). MERRA-2 column dust load for the 04 Feb 2020 (F), 23 Feb 2020 (I) and 28 Feb 2020 (J).
Figure 5. Surface dust and dust$_{2.5}$ concentrations of MERRA-2 reanalysis (26.5-30.0°N, 19.3-12.0°W) and observed (24h average) PM$_{10}$ and PM$_{2.5}$ measured in AQMS during specific days of dx-01, dx-02, dx-03, dx-04 and dx-05 events in the Canary Islands.
Figure 6. Event dx-03. Time series of (24h average) PM$_{10}$ and PM$_{2.5}$ in AQMSs of the Canary Islands and central mainland Spain (mSpain) and dust and dust$_{2.5}$ concentrations ($\mu g/m^3$) obtained with MERRA-2 in the Canary Islands (27-29°N, 15-17.5°W) and central mainland Spain (39-41°N, 6.8-4.3°W). The geopotential height (GPH) of the 850hPa level (B), wind at 1000hPa (C), the satellite image (NOAA-20 VIIRS)(D) and the column dust load (E) are included.

Another two extreme dust events occurred in January 2022 (Fig.7). The dx-04 event impacted on the Canary Islands during 14-17 Jan 2022, resulting in (24h average) PM$_{10}$ and PM$_{2.5}$ concentrations within the range 275-883 $\mu g/m^3$ (Fig.7A1; Fig.5D1) (‘Tenerife, Casa Cuna AQMS) and 60-136 $\mu g/m^3$ (Fig.7A2; Fig.5D2) (‘Tenerife, Caletilla AQMS), respectively. A few days later, the dx-05 occurred (29 Jan - 1 Feb 2022) impacting again the Canary Islands, resulting in (24h average) PM$_{10}$ and PM$_{2.5}$ concentrations within the range 314-1055 $\mu g/m^3$ (Fig.7A1; Fig.5E1) (‘Fuerteventura, El Charco AQMS) and 70-199 $\mu g/m^3$ (Fig.7A2; Fig.5E2) (‘El Charco AQMS), respectively. In both cases a massive dust plume was transported northward, approaching to Spain and Portugal (Fig.7D1-7D2). As in the previous cases, these duxt episodes were caused by a L-to-H dipole meteorology, with an anticyclonic core over Europe expanding to North Africa and a cyclone south of the Canary Islands (Fig.7C1-7C2). In the two events, MERRA-2 clearly overestimated dust concentrations (Fig.7B1-7B2).
Finally, the sixth dust event (dx-06: 15-20 March 2022) first impacted mainland Spain and subsequently the Canary Islands (Fig. 8). The event was also prompted by a meteorological L-to-H dipole, linked to the location of the cyclone *Celia* over Morocco and an anticyclonic core over the central Mediterranean (Fig. 8B). The resulting dusty jet (Fig. 8C-8E) expanded from southeast to northwest mainland Spain on the 15 and 16 March 2022. Once in northern Spain, the dust plume split in two branches, a branch travelled eastward across central Europe tracking the anticyclonic circulation at the north of the high-H (Qor-El-Aine et al., 2022), the other branch travelled southward to the Canary Islands tracking the cyclonic L circulation (Fig. 8E-8F).
Figure 8. Event dx-06. Time series of (24h average) PM$_{10}$ and PM$_{2.5}$ in AQMSs in of Northern (N) (A1-A2: Cantabria and Galicia regions), central-north (CN) (A3-A4: Castilla y León region), central (C) (A5-A6: Madrid + Extremadura + Castilla La Mancha regions) and southern (S) (A7-A8, Andalucía region) mainland Spain and in the Canary Islands (A9-A10). The plots also include surface dust concentrations in these regions obtained with MERRA-2 reanalysis (A1-A10). The geopotential height (GPH) (B) and wind (C) in the 850hPa level, the satellite NOAA-20 VIIRS image and column dust load (E-G) is also included.
Figure 9. Surface concentrations of dust (A1-A3) and dust particles smaller than 2.5 microns (dust2.5) (B1-B3) from 14 to 16 March 2022 in mainland Spain according to MERRA-2 reanalysis. Daily (24h) average concentrations of PM10 (A1-A2) and PM2.5 (B1-B2) measured in AQMSs are shown with black numbers.
In mainland Spain, PM$_{10}$ concentrations experienced a sharp increase, from their regular background levels (10-30 µg/m$^3$) to 24h average PM$_{10}$ and PM$_{2.5}$ values within the range (i) 500-3060 µg/m$^3$ (Fig.8A7) and 100-700 µg/m$^3$ (Fig.8A8) in southern Spain (Andalucía and Murcia regions), (ii) 200-1000 µg/m$^3$ (Fig.8A5) and 60-160 µg/m$^3$ (Fig.8A6) in central Spain (Castilla La Mancha, Madrid and Extremadura regions), (iii) 200-1000 µg/m$^3$ (Fig.8A3) and 60-260 µg/m$^3$ (Fig.8A4) in central northern Spain (Castilla y León region), and (iv) 150-500 µg/m$^3$ (Fig.8A1) and 75-130 µg/m$^3$ (Fig.8A2) in northern Spain (Cantabria and Galicia regions) during the 15-16 March 2022, respectively. After several days traveling across thousands of kilometres, the dust plume impacted in the Canary Islands during 17-20 March 2022 (Fig.8F), resulting in (24h average) PM$_{10}$ and PM$_{2.5}$ values within the range 150-430 µg/m$^3$ (Fig.8A9) and 30-80 µg/m$^3$ (Fig.8A10). A regular (no extreme) dust event impacted southern Spain 24-25 March 2022 (PM$_{10}$ and PM$_{2.5}$: 50-420 µg/m$^3$ and 30-120 µg/m$^3$, respectively) (Fig.8A7-8A8) and the Canary Islands 24-25 March 2022 (PM$_{10}$ and PM$_{2.5}$: 40-80 and 20-35 µg/m$^3$, respectively).

This historic dx-06 event (Fig.1D-1E) started the evening of 14 March 2022 (>21h), with a dust inflow in south-eastern Spain that led to 24h average PM$_{10}$ and PM$_{2.5}$ concentrations within the range 70-260 µg/m$^3$ and 25-43 µg/m$^3$ (Fig.9A1-9B1). On 15 March 2022, mainland Spain was blanketed by the massive dusty airmass (Fig.9A2-9B2), which led to 24h average PM$_{10}$ values of: (i) 3069 µg/m$^3$ (Mediterraneo AQMS; Almería province), 1586 µg/m$^3$ (El Ejido; Almería), 848 µg/m$^3$ (Ronda del Valle; Jaén), 621 µg/m$^3$ (Palacio de Congresos; Granada) and 587 µg/m$^3$ (Mompean; Murcia) in south-eastern Spain and 518 µg/m$^3$ in central southern Spain (Sierra Norte; Seville), (ii) 949 µg/m$^3$ (Villa del Prado; Madrid), 944* µg/m$^3$ (Segovia-2; Segovia), 928 µg/m$^3$ (Medina del Campo; Valladolid), 841* µg/m$^3$ (Avila-II; Avila) and 825 µg/m$^3$ (Salamanca-6; Salamanca) in central Spain, and (iii) 808* µg/m$^3$ (Lario; León), 562 µg/m$^3$ (León-01; León), 472 µg/m$^3$ (Laza; Orense) and 371 µg/m$^3$ (Los Tojos; Cantabria) in north-west Spain (Fig.9A2). Some of these PM$_{10}$ concentrations (highlighted with asterisk*) are actually slightly underestimated due to the automatic PM$_{10}$ monitor reached the saturation level (1000 µg/m$^3$) during a few hours and the duxt-r reconstruction method could not be applied to the lack of parallel PM$_{2.5}$ data. On 15 March 2022, the 24h average PM$_{2.5}$ values reached values of (Fig.9B2): (i) 688 µg/m$^3$ (Mediterraneo; Almería), 164 µg/m$^3$ (Ronda del Valle; Jaén), 158 µg/m$^3$ (Palacio de Congresos; Granada) in south-eastern Spain, (ii) 252 µg/m$^3$ (Salamanca-6), 153 µg/m$^3$ (Medina del Campo; Valladolid) and 119 µg/m$^3$ (Villa del Prado; Madrid) in central Spain and (iii) 129 µg/m$^3$ (Laza; Orense) in north-west Spain. During the 16 March 2022, high PM$_{10}$ and PM$_{2.5}$ values were still recorded (Fig.9A3-9B3), with the highest PM$_{10}$ concentrations linked to the still ongoing dust inflow by south-eastern Spain: 800 µg/m$^3$ (Bailén; Jaén), 774 µg/m$^3$ (Ronda del Valle; Jaén), 535 µg/m$^3$ (Mediterraneo; Almería) and 432 µg/m$^3$ (El Ejido; Almería). During the dx-06 event, the hourly PM$_{10}$ concentrations exceeded 2000 µg/m$^3$ at four sites which reached maximum PM$_{10}$ values: 4573* µg/m$^3$ (Mediterraneo; Almería), 3502 µg/m$^3$ (El Ejido; Almería), 2813 µg/m$^3$ (Mompean; Murcia) and 2154 µg/m$^3$ (Ronda del Valle; Jaén) (Fig.2C3). Similarly, the hourly values of PM$_{2.5}$ exceeded 400 µg/m$^3$ at four sites, where the maximum 1h PM$_{2.5}$ concentration were:
1000* µg/m³ (Mediterraneo; Almería, PM$_{2.5}$ analyzer saturated), 471 µg/m³ (Mompean; Murcia), 443 µg/m³ (Salamanca-6), 400 (Ronda del Valle; Jaén). On 15 March, hourly PM$_{2.5}$ concentrations at Mediterraneo AQMS saturated at 1000 µg/m³ during 6 hours (08-13h), so the daily average PM$_{2.5}$ value = 688 µg/m³ at this site is actually somewhat underestimated and consequently also the daily average PM$_{10}$ value = 3069 µg/m³ (obtained with the duxt-r method).

3.3 Record breaking events

The analysis of the 2000-2022 time series of (24h average) PM$_{10}$ (Fig.10) and PM$_{2.5}$ (Fig.11) data, evidence that the duxt events we report here are record beating episodes in Spain, both for mainland Spain and the Canary Islands. The massive dusty airmass that blackened mainland Spain during the 15 and 16 of March 2022 (dx-06; Fig.10 and 11) resulted in the highest PM$_{10}$ and PM$_{2.5}$ concentrations ever recorded in the regional scale across northern Spain (Cantabria region; Fig.10A), central-northern Spain (Castilla y León region; Fig. 10C & 11A), central Spain (Castilla La Mancha, Extremadura and Madrid region; Fig.10D & 10A) and southern Spain (Andalucía region; Fig. 10E, 10F & 11C). For example, in central Spain (Castilla La Mancha + Extremadura + Madrid), regular Saharan dust events typically induce (24h average) PM$_{10}$ concentrations within the range 40-140 µg/m³ (highlighted with black arrows in Fig.10D) (Pey et al., 2013; Rodríguez et al., 2001), whereas during the dx-06 event 33 AQMSs of this region recorded (24h average) PM$_{10}$ concentration within 300-949* µg/m³ ("Villa del Prado AQMS in Madrid region") (white arrow in Fig. 10D). After analysing the 2001-2011 time series, Pey et al. (2013) concluded that in the Western Mediterranean, Saharan dust events inducing PM$_{10}>100$ µg/m³ (24h average) are actually rare. The impact of the dx-06 event is not observed in Cataluña since it did not reach Northeast Spain (Fig.10B).
Figure 10. Time series (2000-2022) of (24h average) PM$_{10}$ concentrations of 118 AQMSs distributed across northern (N; 3 AQMSs), North-East (NE; 8 AQMSs), Central-North (CN; 30 AQMSs), Central (C; 35 AQMSs), Southwest (SW; 16 AQMSs) and Southeast (SE; 11 AQMSs) mainland Spain and in the Canary Islands (15 stations). Black arrows indicate regular dust events. White arrows indicate the duxt events. The asterisk indicates the intense event occurred 22 Feb 2016.
Figure 11. Time series (2000-2022) of (24h average) PM$_{2.5}$ concentrations of in a total of 74 AQMSs distributed across the Central-North (CN; 4 AQMSs), Central (C; 16 AQMSs) and Southeast (S; 10 AQMSs) mainland Spain and in the Canary Islands (44 stations). Black arrows indicate regular dust events. White arrows indicate the duxt events.
In the Canary Islands, the most intense Saharan dust events ever recorded occurred in the period 2020-2022 linked to the duxt events described in this study. Since 2005 to 2020, intense Saharan dust events have regularly been associated with (24h average) PM$_{10}$ and PM$_{2.5}$ values with 200-400 µg/m$^3$ (Fig.10G) and 100-200 µg/m$^3$ (Fig.10D), respectively. This PM$_{10}$ range is similar to (1) that of total suspended particles during Saharan dust events of the period 1998-2003, based on AQMS data not yet normalised to the European standards (Alonso-Pérez et al., 2007, 2012; Viana et al., 2002), and to (2) that of total dust at Izaña Observatory (Tenerife) during the 1987-2014 Saharan dust events (Rodríguez et al., 2015). In contrast, in the period 2020-2022, the duxt events described here led to PM$_{10}$ and PM$_{2.5}$ concentrations within the ranges 600-1840 µg/m$^3$ (Fig.10G) and 200-404 µg/m$^3$ (Fig.11D), respectively. The three most intense dust events ever recorded in the Canary Islands, exceeding the threshold of 600 µg/m$^3$ of PM$_{10}$ as 24h average, in descending order of magnitude, are:

1. dx-02 event: the 23 and 24 Feb 2020 the (24h average) PM$_{10}$ averaged in all AQMSs were 531 and 930 µg/m$^3$ (averages of 34 AQMSs distributed in the 7 Canary Islands), respectively. The 22, 23 and 24 Feb 2020, a total of 6, 25 and 12 AQMSs recorded a (24h average) PM$_{10}$ concentration between 600 and 1840 µg/m$^3$ (*Gran Canaria, Playa del Inglés AQMS). Previous to this event, the (24h average) PM$_{10}$ concentrations had only exceeded 600 µg/m$^3$ in just one AQMS (618 µg/m$^3$ at Las Galanas during the dust event 28 March 2018; Fig.10G).

2. dx-05 event: 29 and 30 Jan 2022 the (24h average) PM$_{10}$ averaged in all the AQMSs was 463 and 501 µg/m$^3$ (averages of 44 AQMSs distributed in the 7 islands). The 29 and 30 of Jan 2022, a total of 9 and 10 AQMSs recorded a (24h average) PM$_{10}$ concentration between 600 and 1055 µg/m$^3$ (*Fuerteventura, El Charco AQMS).

3. dx-03 event: the 16 Feb 2021 the (24h average) PM$_{10}$ averaged in all AQMSs was 463 µg/m$^3$ (average of 36 AQMSs distributed in the 7 islands). The 16 Feb 2021, 4 AQMSs recorded a (24h average) PM$_{10}$ concentration between 600 and 638 µg/m$^3$ (*Las Galletas AQMS, Tenerife).

In mainland Spain, the dx-06 is the most intense dust event ever recorded. A total of 20 AQMSs, distributed across south-eastern, central to central-northern Spain, registered (24h average) PM$_{10}$ concentrations within the range 600 to 3069 µg/m$^3$ (*Mediterraneo AQMS in Almeria province). The 2 decades time series of PM$_x$ also offer other interesting data. In many of regions of Spain there is a clear 2000-2020 decreasing trend of PM$_{10}$ concentrations linked to the reduction of emissions following air quality policies (Fig.10A, 10C, 10E) (Li et al., 2018; Querol et al., 2014).
3.4 Meteorological anomalies linked to duxt events

The 2020-2022 six duxt events we report here were induced by the L-to-H meteorological dipoles formed by cyclones located at the southwest of a blocking anticyclone over western Europe. Fig. 12 (A1 to F1) show the anomaly of the 500 hPa geopotential height during the onset of the six duxt events studied here (Fig.12 A2 to F2). All duxt events occurred during northern-hemisphere meteorological anomalies that resemble the anomalies of the atmospheric circulation linked to the anthropogenic global warming (Fig.12): (i) subtropical anticyclones intensified and expanded to higher latitudes (Cherchi et al., 2018; Cresswell-Clay et al., 2022), (ii) anomalous low pressures expanding northward beyond the tropical belt, resembling the tropical expansion (Seidel et al., 2008; Yang et al., 2020, 2023) (e.g. dx-01, dx-02, dx-03 and dx-04) and (iii) mid-latitudes amplified undulation of the Rossby waves due to the concatenation of cut-off lows - cyclones and anticyclones pointing to a weakening of the polar vortex (e.g. dx-03, dx-05, dx-06 and 23-mar-2022) (Mann et al., 2017). The duxt events observed at the Eastern Mediterranean in March 2018 (Solomos et al., 2018), at North Africa in June 2020 (Bi et al., 2023; Francis et al., 2020), at Uzbekistan in November 2021 (Xi et al., 2023) and in China in March 2021 (Gui et al., 2022), occurred in this context of cyclones, blocking anticyclones and dipoles linked to mid-latitudes amplified Rossby waves.

The winter blocking anticyclone that we observed over western Europe/Western Mediterranean during the duxt events (Fig.12A1-G1) fits with the picture of the industrial-era eastward expansion of the North Atlantic anticyclone starting in the 1850s and accelerating in the last few decades (Alonso-Pérez et al., 2011b; Cresswell-Clay et al., 2022), a trend that is expected to continue as the concentrations of greenhouses gases increase, according to the CMIP5 multi-model simulations (Cherchi et al., 2018); the low pressures at the southwest of the blocking anticyclone that we observe during the duxt events (Fig.12B1-12E1) are expected to follow as the tropic expands northward off North Africa in the forthcoming decades (e.g. see Fig 1F of Cherchi et al. 2018 for the 2075-2100 period).

The anomalies linked to the duxt events are also evident in the trajectory of the cyclones that finally form the L-to-H dipoles leading to the extreme dust emissions. Red circles in Fig.12A1-12G1 indicate the location of the cyclones from days before (negative number) to days after (positive number) of the duxt event. Due to the anticyclonic blocking over western Europe, the mid-latitudes North Atlantic cyclones didn’t follow their regular path across Europe or the Mediterranean. The cut-off lows forming the L-to-H dipoles reached this region (Canary Islands, Cape Verde or inner Sahara) by two main paths:
Figure 12. Anomaly (A1-G1) of the 500 hPa geopotential height (GPH) (respect to the 1991-2020 climatology) and column dust in the onset of the dx-01 to dx-06 and 24-26 March 2022 events (A2-G2). Red circles (A1-G1) indicate the location of the cyclones days before (negative number) to days after (positive number) the first day of the duxt event.
1. they deviated southward from the North Atlantic mid-latitudes as results of the blocking anticyclone over western Europe; subsequently these cut-off lows may stay during long periods (up to 12 days) in the subtropical and tropical north-east Atlantic (near the Canary Islands and Cape Verde). This is the case of the dipoles of events dx-02, dx-04, dx-05 and dx-06, and also of the intense dust event of 23 March 2022. The cyclones of the events dx-02, dx-04 and dx-05 stayed (blocked by the anticyclonic situation) near the Canary Islands and Cape Verde during 10, 12 and 8 days (Fig. 12B1, 12D1 and 12E1), respectively.

2. they deviated northward from the tropical belt. This is the case of the events dx-01 and dx-03, associated with cyclones which had moved from Cape Verde to the west of the Canary Islands (Fig. 12A1, dx-01) and to the inner Sahara (Fig. 12C1, dx-03), respectively, across a tropical band anomalously shifted to northward.

4 Summary and conclusions

In winter 2020, 2021 and 2022 a set of six extreme dust events expanded northward from NW Africa to the Atlantic and Europe, causing extremely high concentrations of PM$_{10}$ and PM$_{2.5}$ in the Governmental Air Quality Monitoring Stations of the Canary Islands and mainland Spain, up to exceeding the upper operation limit of many PM$_{10}$ monitors. We developed the duxt-r methodology for assessing the consistency of the PM$_{10}$ and PM$_{2.5}$ data and re-construct the underestimated PM$_{10}$ concentrations. During these extreme dust events, the 1-hour average PM$_{10}$ and PM$_{2.5}$ concentrations were within the range 1000-6000 µg/m$^3$ and 400-1200 µg/m$^3$, whereas the 24-h average PM$_{10}$ and PM$_{2.5}$ data were within the range 500-3070 µg/m$^3$ and 200-690 µg/m$^3$, respectively. These extreme dust episodes are caused by the intense winds associated with the meteorological dipoles formed by a blocking anticyclone over western Europe and a cut-off low - cyclone located at the southwest, near the Canary Islands, Cape Verde or into the Sahara. The analysis of the 2000-2022 time series of PM$_{10}$ and PM$_{2.5}$ shows that these events have no precedent in Spain. Record breaking PM$_{10}$ and PM$_{2.5}$ (24h average) concentrations were measured in the Canary Islands during the 22-24 February 2020, 1840 µg/m$^3$ and 404 µg/m$^3$, and in mainland Spain during 15-16 March 2022, 3069 µg/m$^3$ and 688 µg/m$^3$ (Almeria province), respectively. All duxt events occurred during northern-hemisphere meteorological anomalies associated with subtropical anticyclones intensified and expanded to higher latitudes, anomalous low pressures expanding beyond the tropical belt and a concatenation of cut-off lows and anticyclones suggesting to a weakening of the polar vortex, with features that resemble the change in the atmospheric circulation linked to climate change. These events occurs in the context in which climate projections forecast the expansion of the North African drylands toward the northwest, increasing the risk of desertification of Spain. The air quality monitoring networks need to adapt the strategy and operation range of the PM$_{10}$ and PM$_{2.5}$ monitoring programs to ensure accurate measurements can be done during
these extreme dust events due to the importance of having suitable data in the public data sets for health effects studies, modelling, etc…

Data availability

The data used in the manuscript are available in public data bases, including the PM$_{10}$ data reconstructed as result of this study. Data are also available by request to the first author at sergio.rodriguez@csic.es

Author contributions

SR and JLD performed the conceptualisation, investigation, data collection, treatment and formal analysis. SR wrote the original version of the manuscript, which was subsequently revised and edited by SR and JLD.

Competing interests

The authors declare that they have no conflict of interest.

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