

Supplement of

Sharp increase of Saharan dust intrusions over the Western Mediterranean and Euro-Atlantic region in winters 2020-2022 and associated atmospheric circulation.

Cuevas-Agulló et al.

Correspondence to: Sara Basart (sbasart@wmo.int)

S1. Extreme dust events

In this section, we take a closer look at the most intense events identified in the 2003-2022 period and mentioned in the present analysis. The events analysed in detail occurred on 20-24 February 2017, 27-31 March 2021, and 15-31 March 2022. Those in 2021 and 2022 were also analysed in detail by different international institutions (see Table S1) because the social media impact.

Table S1: Links to web news and technical report previews on strong wintertime dust intrusions over Western Europe in the 2020-2022 period (last access to all links on 18 September 2022).

Dust event	Entity issuing the news and source
Feb 2020	EUMETSAT: https://www.eumetsat.int/dust-over-canaries WMO: https://public.wmo.int/en/media/news/wmo-issues-airborne-dust-bulletin
Feb 2021	Copernicus: https://atmosphere.copernicus.eu/saharan-dust-colours-skies-and-snow Copernicus: https://atmosphere.copernicus.eu/2021-review-cams-goes-strength-strength 20 EUMETSAT: https://www.eumetsat.int/dust-over-south-eastern-europe EUMETSAT: https://www.eumetsat.int/meteosat-11-captures-saharan-dust-plume-from-northern-africa WMO: https://public.wmo.int/en/media/news/sand-and-dust-storm-hits-europe BSC: https://www.bsc.es/news/bsc-news/exceptional-february-europe-terms-saharan-dust-intrusion-episodes
Mar 2022	Copernicus: https://atmosphere.copernicus.eu/historical-saharan-dust-episode-western-europe-cams-predictions-accurate EUMETSAT: https://www.eumetsat.int/widespread-dust-intrusion-across-europe EUMETSAT: https://www.eumetsat.int/dust-over-south-eastern-europe

25

The associated synoptic situation in each of the three cases are described using NCEP/NCAR (see Section 2). The temporal evolution of the geopotential height (Z, in m) at 500 hPa (Z500) for each one of the three “extreme” dust events in the whole period 2003-2022 are shown in Figure S1. Averaged Z anomalies (m) at 925, 500, 200 hPa for each of the same five dust events are shown in Figure S2. Additionally, the analysis of these particular cases includes in-situ PM10 observations from European Environment Agency’s air quality database (AirBase; <https://www.eea.europa.eu/data-and-maps/data/aqereporting-9>, last access 15 June 2023), satellite qualitative aerosol products based on the EUMESAT dust red–green–blue (RGB) image

animations from Meteosat Second Generation (MSG) Spinning Enhanced Visible and InfraRed Imager (SEVIRI) and daily dust forecasts based on MONARCH (<https://duast.aemet.es/about-us/monarch>, last access 15 July 2023) which is the reference operational forecast system at from the WMO Barcelona Dust Regional Center (<https://dust.aemet.es/about-us/wmo-dust-operations>).

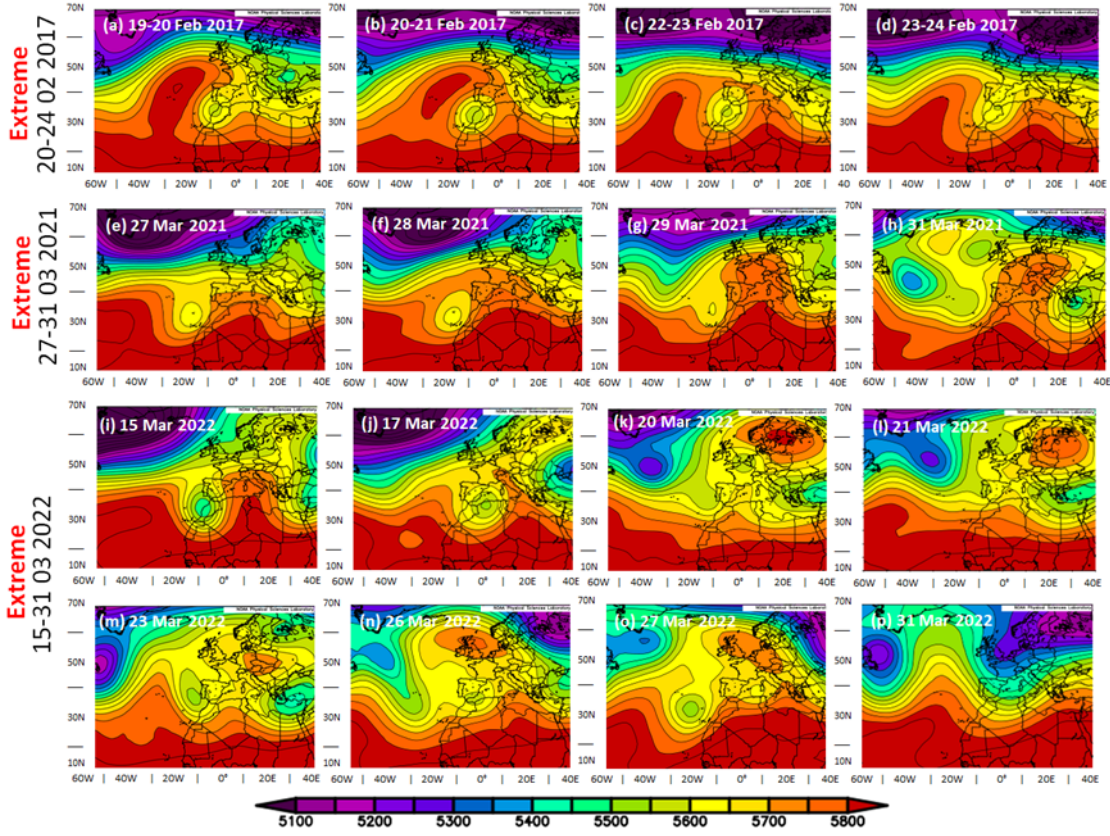


Figure S1: Geopotential height fields (Z) at 500 hPa from NCEP reanalysis for sub-periods of time of the three strongest dust events occurred in the geographical domain of study on Feb. 20-24, 2017 ((a), (b), (c) and (d)); Mar. 27-31, 2021 ((e), (f), (g) and (h)); and Mar. 15-31, 2022 ((i), (j), (k), (l), (m), (n), (o), and (p)). Geopotential height fields have been obtained from NCEP/NCAR reanalysis.

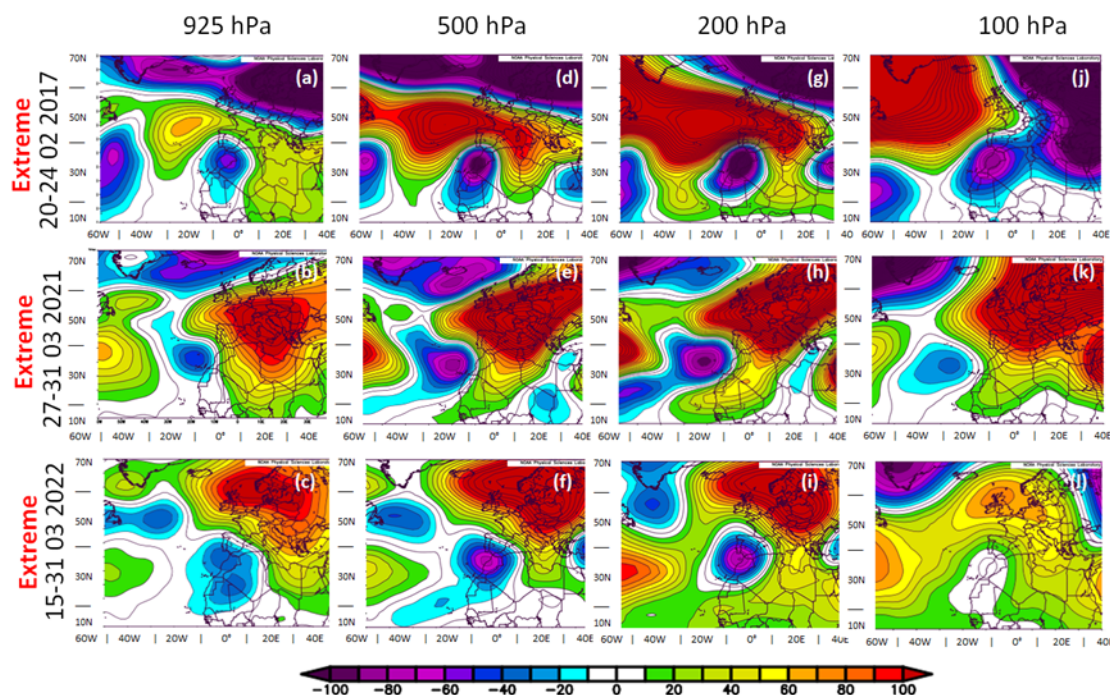
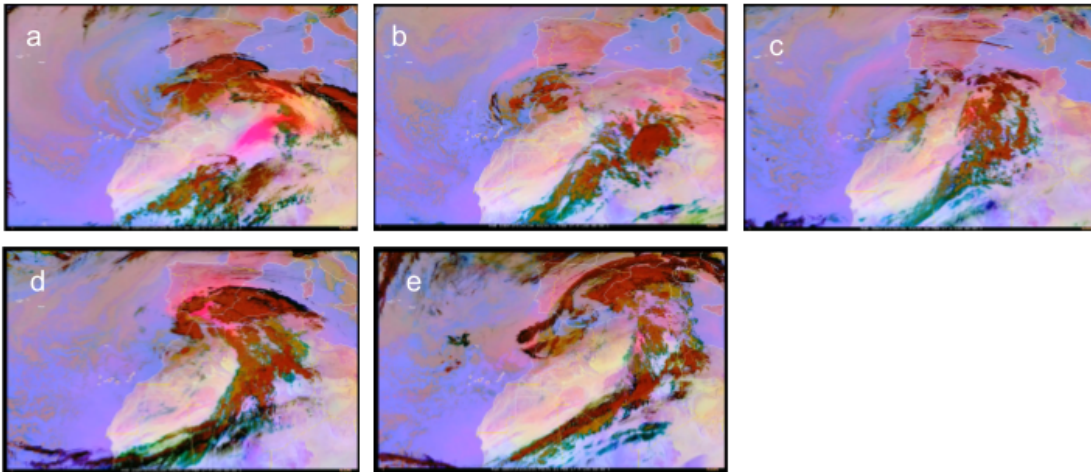


Figure S2: Geopotential height (Z) anomalies (m) at 925 hPa ((a),(b) and (c)), 500 hPa ((d), (e) and (f)), 200 hPa ((g),(h) and (i)), and 100 hPa ((j), (k) and (l)), with respect to the reference period 1991-2020, for the three strongest dust events occurred in the geographical domain on the following dates: Feb. 20-24, 2017; Mar. 27-31, 2021; and Mar. 15-31, 2022. Geopotential height fields have been obtained from NCEP/NCAR reanalysis.

S1.1. Case analysis #1: February 2017

Fernandez et al. (2019) describe this episode from episode by episode from the approximation of optical properties of aerosols, qualifying it as "an unprecedented extreme Saharan dust event" that mainly affected the Iberian Peninsula where AOD above 2 were measured at several sunphotometers of the global NASA AERONET network (Holben et al., 1998; Giles et al., 2019). This 5-day dust event yielded median and mean AOD values of 0.31 and 0.41 respectively in our study region. This dust event that lasted 5 days in our study region. The intrusion over Europe was caused by a cut-off low detached from the general circulation because due to the interaction with a long and intense ridge over the North Atlantic, which that reached the British Isles, located in its western part (Figure S1 (a), (b), (c), and (d)). It is noteworthy that the Z anomalies for each day of the event (not shown here) and those averaged over the 5 days of the event are very similar throughout the troposphere, from near ground level close to the ground (925 hPa; Figure S2 (a)) to the lower stratosphere (100 hPa; Figure S2 (j)), registering negative values < -100 m between 500 and 200 hPa where the cut-off low basis found, and on the contrary, positive values, > +100 m, in a large strip that extends from the mid-latitude North Atlantic to western and central Europe, forming a persistent dipole like-pattern configuration. The cut-off low was initially centred on the NW of Morocco on February 20 (Figure S1 (a)) with slow retrograde movement towards the SW that caused dust rise from the mountainous areas of the NW of Algeria as seen from the RGB-SEVIRI animation (Figure S3), which produced a low-density dust plume towards the south of the Iberian Peninsula that can be clearly identified with a pink colour. Later, on 21 February dust was uplift from the interior of Algeria, producing a denser dust plume (stronger pink colour) towards the Mediterranean. On 22 February, dust sources between NE Morocco and NW Algeria activated significantly increasing dust amount transported to the south of the Iberian Peninsula. In its final phase, the low was absorbed by the mid-latitude circulation.

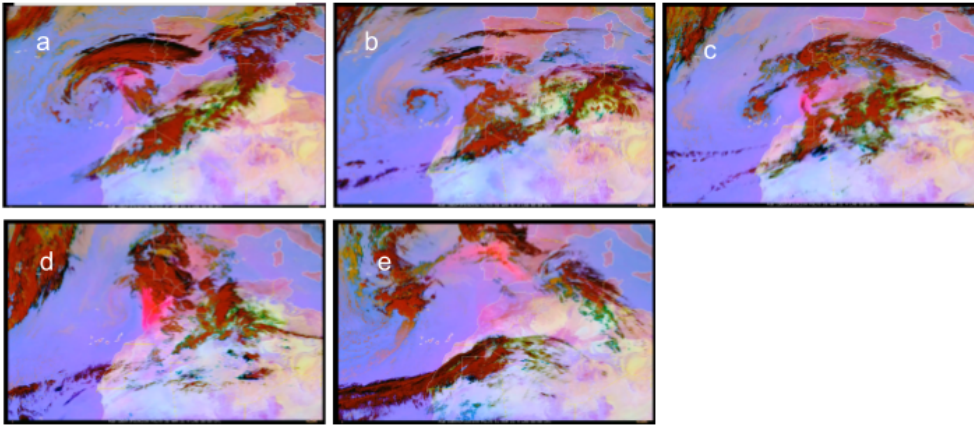
A “moderate” event on 18-22 February 2017 showed similar synoptic situation (not shown here). This dust event was the subject of a detailed analysis by Oduber et al. (2019), which described this event as “unusual”. However, these authors did not report that the cause of this dust intrusion was a stationary cut-off low centred on the Atlantic coast of Morocco.



70 **Figure S3: RGB dust product from MSG/SEVIRI at 0UTC for (a) 20 February 2017, (b) 21 February 2017, (c) 22 February 2017, (d) 24 February 2017, and (e) 24 February 2017. Dust is associated to pink colour.**

S1.2 Case analysis #2: March 2021

On March 27 began a 5-day dust event with AOD median and mean AOD values of 0.39 and 0.41, respectively, values that cause it to be labelled as "extreme", the second chronologically in this category in the series of dust events since 2003. Isolated cut-off low centred over Madeira and combined with a strong ridge over Western Mediterranean and France (Figure S1 (e)), favoured dust transport from Morocco and Mauritania to SW Iberian. At the end of this long dust event an Omega block centred on Western Europe on the 29th was established (Figure S1 (g)). An intense dust lift is then produced at the lee of the Atlas Mountains (south Morocco), a dust hot-point (Schepanski et al., 2012; Fiedler et al., 2014), generating a very dense dust plume that moved to the North that crossed the entire west half of the Iberian Peninsula until the North Atlantic impacting the south of British Islands and later Belgium (Figure S4). Again, during this event, a dipole like-pattern of Z anomalies, with positive anomalies over Western Europe and negative anomalies from the persistent cut-off low, like those of previous cases, is well observed in the whole troposphere (Figure S2 (b), (e), (h), and (k)).



85 **Figure S4: RGB dust product from MSG/SEVIRI at 0UTC for (a) 27 March 2021, (b) 28 March 2021, (c) 29 March 2021, (d) 30**
 90 **March 2021, and (e) 31 March 2021. Dust is associated to pink colour.**

S1.3 Case analysis #3: March 2022

90 The very long 14-day lasting dust event of March 2022 (see Figure S5), with an AOD median and mean AOD values of 0.34
 and 0.40, respectively, constitutes a milestone in the dust transport from North Africa to the Western Mediterranean and the
 Euro-Atlantic region, impacting air quality of western Europe with rather high PM10 values (Figure S6). This event has broken
 all records, both not only for duration and, intensity but also for the, and area affected. This long dust event was due to the
 concatenation of a series of cut-off lows centred located on close locations between the Canary Islands and the Iberian Peninsula
 caused by due to a persistent anticyclonic blocking over Western Europe (see the sequence of eight plots in Figure S1 (i), (j), (k), (l),
 95 (m), (n), (o), and (p)). In fact, this long dust event was initiated by the slow movement of the storm named Celia (cut-off low #1)
 over the North African coast from 14 to 16 March (see Figure S5 (a) and (b)). Celia began to lose intensity in the second half of the
 15th and ceased to be named as such on the synoptic maps, although it (cut-off low #1) continued a gradual transition towards the
 Mediterranean region over through the north of the African continent (see movement of Celia/cut-off low #1 in Figure S1 (i) and (j)),
 which remained isolated from the general circulation. Cut-off low #1, with forcing on its SE flank, produced a dense plume of dust
 that, at times, was difficult to identify among abundant cloudiness, which moved moving from the interior of Algeria towards the N-
 100 NW of the Iberian Peninsula reaching the North Atlantic and impacting France (see Figure S5). The dust plume that reached
 southwestern France on the early 15th, was already at 50°N 12 hours later, curving then to the East and moving at higher
 altitude, impacting central Europe (Figure S7 (a)) (cross section March 15 at 12 UTC). On the 16th at 3 UTC a second branch
 of the same dust plume curved to the southwest, returning to the African continent along the NW coast of Morocco (Figure S7
 105 (b)) (March 16 at 03 UTC). Cut-off low #1 severely impacted the Iberian Peninsula, as can be seen by comparing the map of
 PM10 concentrations in Europe on March 13 (pre-intrusion), in which most of the stations of the Iberian Peninsula and the
 Balearic Islands show concentrations of $\text{PM}_{10} \leq 20 \mu\text{g}\cdot\text{m}^{-3}$ and that of March 15 in which many of these stations recorded
 concentrations of $\text{PM}_{10} > 150 \mu\text{g}\cdot\text{m}^{-3}$ (Figure S6 (a), (b)). The dust advection on the Peninsula subsided as of the second half
 of the 16th. However, cut-off low #1 continued advecting dust over the western Mediterranean from sources near the Algerian
 coast until the arrival of a second deep low (cut-off low#2). The strong convection of the cut-off low#1 on 14-16 March was
 110 responsible for the significant thickness of the dust layer and the high level of dust transport (~ 5000 m height) impacting the
 Pyrenees and the Alps (Figure S7 (b)) (cross section March 16 at 3 UTC). Cut-off low #2 was centred on the 20th (Figure S1
 (k)) over the coast of Morocco but remained stationary without advancing further to the E, generating limited dust transport
 over the Mediterranean. Cut-off low #3 on the 23rd (Figure S1 (m)) followed similar evolution to the first one, but without
 115 penetrating its circulation so much in the continent in such a way that it raised mineral dust from plateau areas of the Algerian

Atlas being only advected to the south of the Iberian Peninsula (Figure S2 (c)), while cut-off low#3 weakened and moved to the Mediterranean. Finally, from 27th, the last deep low (cut-off low #4), more extensive, came down very close to the Canary Islands and in its shift to the E raised dust again from the NW of Algeria plateaus, advecting dust to the western Mediterranean and impacting the Iberian Peninsula, the Balearic Islands, France, North Italy, Belgium, and western Germany increasing dramatically, again, the PM10 concentrations ($PM_{10} > 50 \mu g \cdot m^{-3}$) in many European air quality stations (see PM10 concentrations on Europe in March 29th; Figure S2 (d)). On the 30th, already in its final phase, cut-off low #4 produced new dust plumes from the river drainage basin of the Aïr around the Saharan mountain ranges in southern Algeria, moving towards the Central Mediterranean, while generating a huge dust front associated with a haboob in central Algeria. Meanwhile the strong ridge over Europe continued until the last days of March, not so intense, and disappearing at the west of the British Islands. As in the four previous cases, a dipole pattern of Z anomalies is observed throughout the troposphere, with positive values covering a wide band over Europe and the North Atlantic, and negative anomalies in the region between the Canary Islands and the Iberian Peninsula (Figure S2 (c), (f), (i), and (l)). In this case, since it is a very long period, the train of three cut-off lows can be observed at 500 and 200 hPa (Figure S2 (f) and (i)).

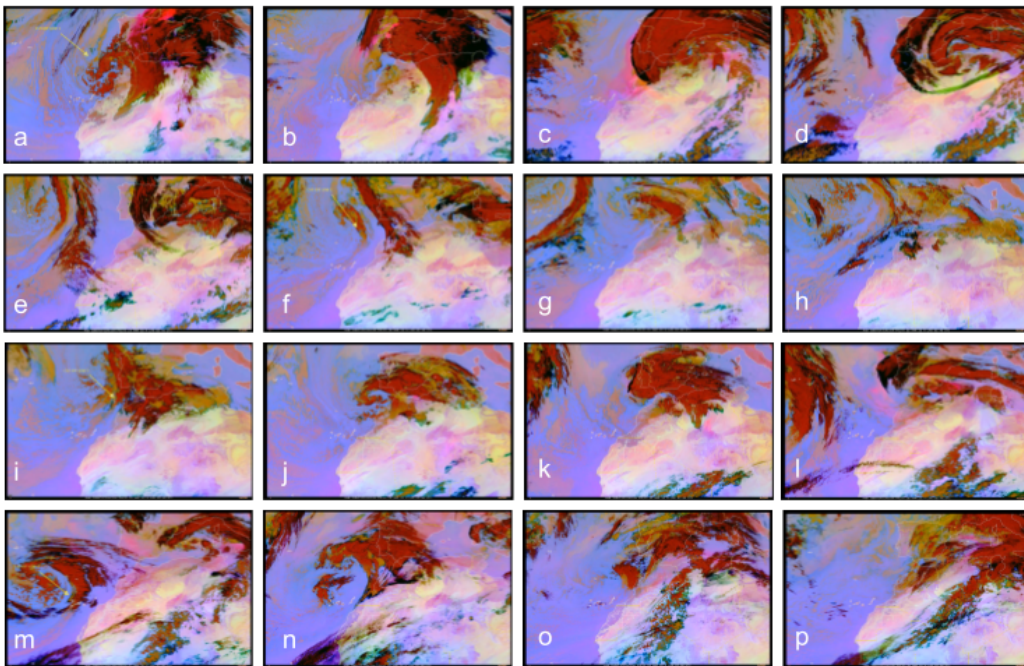


Figure S5: RGB dust product from MSG/SEVIRI at 3UTC for (a) 15 March 2022, (b) 16 March 2022, (c) 17 March 2022, (d) 18 March 2022, (e) 19 March 2022, (f) 20 March 2022, (g) 21 March 2022, (h) 22 March 2022, (i) 23 March 2022, (j) 24 March 2022, (k) 25 March 2022, (m) 26 March 2022, (n) 27 March 2022, (o) 28 March 2022 and (p) 29 March 2022. Dust is associated to pink colour.

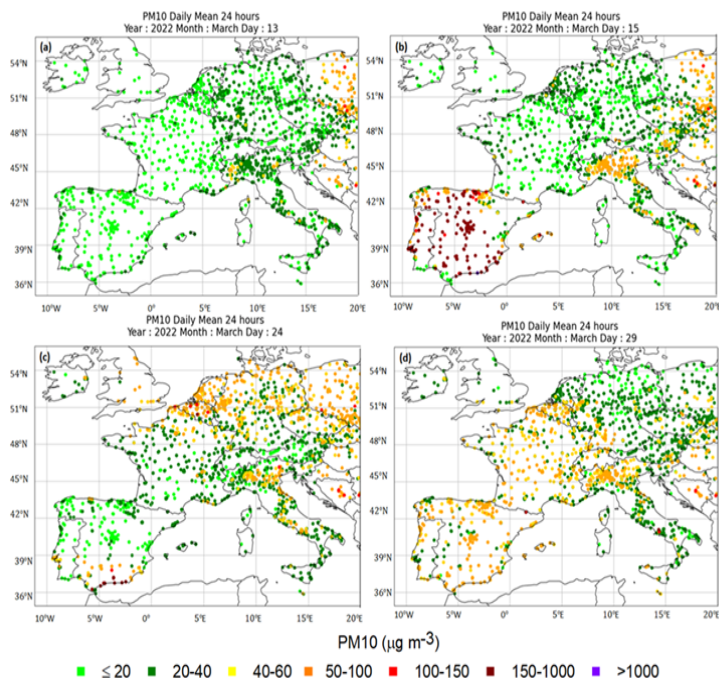


Figure S6-3: Daily mean PM10 ($\mu\text{g m}^{-3}$) at the European stations on (a) 13 March 2022, (b) 15 March 2022, (c) 24 March 2022, and (d) 29 March 2022. Data from the European Environment Agency (EAA).

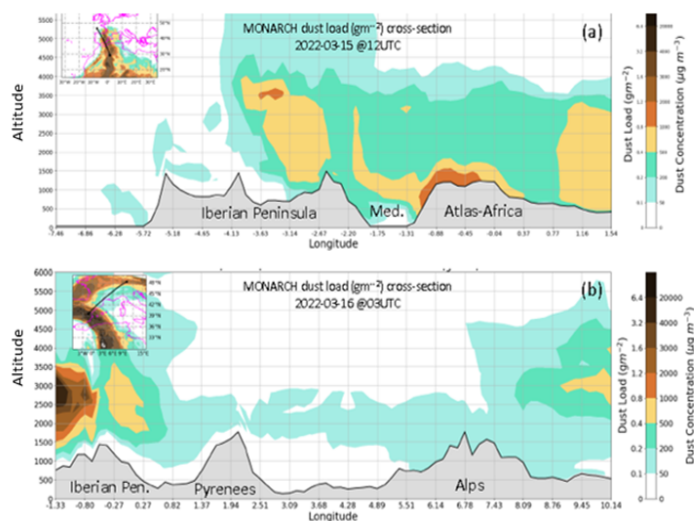


Figure S7: Forecasted vertical cross-sections and dust concentration ($\mu\text{g m}^{-3}$) (dust load (g m^{-2})) on (a) 15 March 2022 at 12 UTC and on (b) 16 March 2022 at 3 UTC. Dust forecast from MONARCH.

S2. AOD intercomparison

The present study includes different AOD databases coming from satellite aerosol retrievals (i.e MODIS, see Figure S8 and S9) and reanalysis. To ensure the consistency of the results, here we perform a comparison between MERRA-2 and MODIS (Figure S9 and Figure S10), but also between MODIS and AERONET (Table S2).

MODIS shows higher AODs for 2020-2022 (median of 0.36 and maximum of 0.35) than 2003-2019 (median of 0.21 and maximum of 0.49) (see Figure S8). The number of dust events for each month (Jan, Feb, Mar) and each year of the period

150

2003-2022, the number of days each dust event lasts, and its average AOD, have been obtained from MERRA-2 following the same methodology as that using AOD from MODIS (see section 2.1). In Figure S9 are shown together the results for MODIS and MERRA-2 that indicate very similar features and patterns of evolution of dust events in the whole period 2003-2022.

155

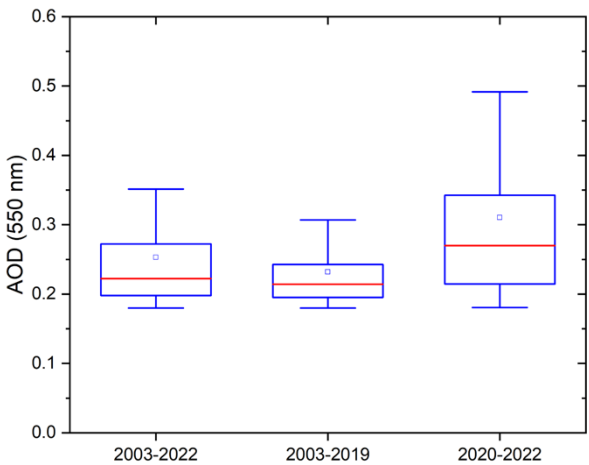


Figure S8: Box-plot of AOD for the three study periods (All: 2003-2022; Period 1: 2003-2019 and Period 2: 2020-2022). Lower and upper boundaries for each box are the 25th and 75th percentiles; the red line is the median value; the dot blue is the mean values; and hyphens are the maximum and minimum values. Results are based in MODIS aerosol retrievals.

160

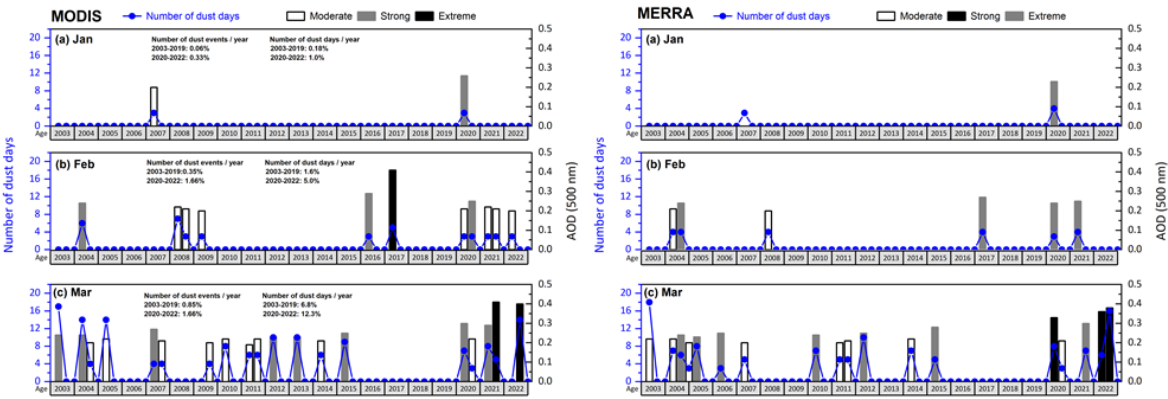


Figure S9: Number of dust days (blue dots and lines; left y-axis), and average AOD (bars; right y-axis) for (a, d) January, (b, e) February, and (c, f) March in the period 2003-2022 for MODIS and MERRA-2, respectively. The colour of the bars indicates the type of the dust event.

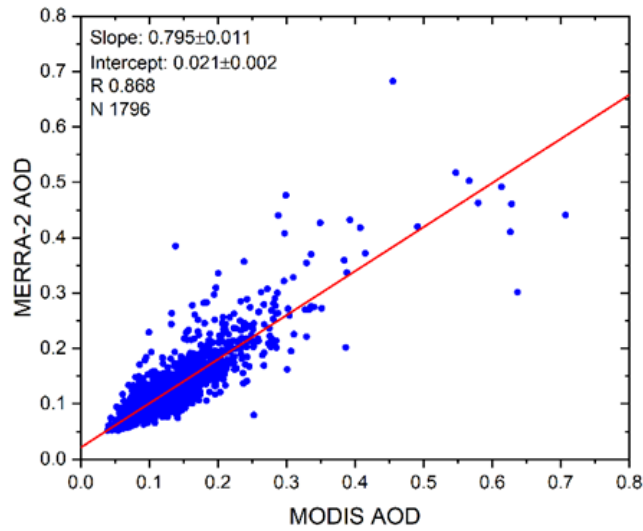


Figure S10: Scatterplot of MERRA-2 AOD versus MODIS AOD between 2003 and 2022 considering only the dust days. The red solid line is the least-square fit. The least-square fit is show in the legend. R is correlation coefficient Pearson and N is the number of days.

AERONET direct-sun Version 3 cloud-screened AOD data (Giles et al., 2019) of five stations in Europe (Figure S11) are compared with MODIS AOD data. For the comparison is used the closest MODIS pixel to the AERONET station. The results show a good correlation between Évora and Palencia AERONET and MODIS AOD with values of bias ≈ 0.001 -0.002 and Pearson coefficient (R) >0.6 . For Arenosillo, Palma de Mallorca, and Toulouse, R is ≈ 0.4 (Table S2).



Figure S11: Location of the AERONET stations used in this study.

Table S2: Statistics for the bias (MODIS AOD - AERONET AOD) and Pearson coefficient (R) between MODIS and AERONET AOD for five AERONET stations. Their location is shown in Figure S11.

AERONET Station	Period of data	Bias	Pearson (R)
Arenosillo	13/03/2003 – 31/03/2022	-0.080	0.47
Évora	15/02/2004 – 27/03/2022	-0.002	0.64
Palencia	15/02/2004 – 31/03/2022	+0.001	0.67

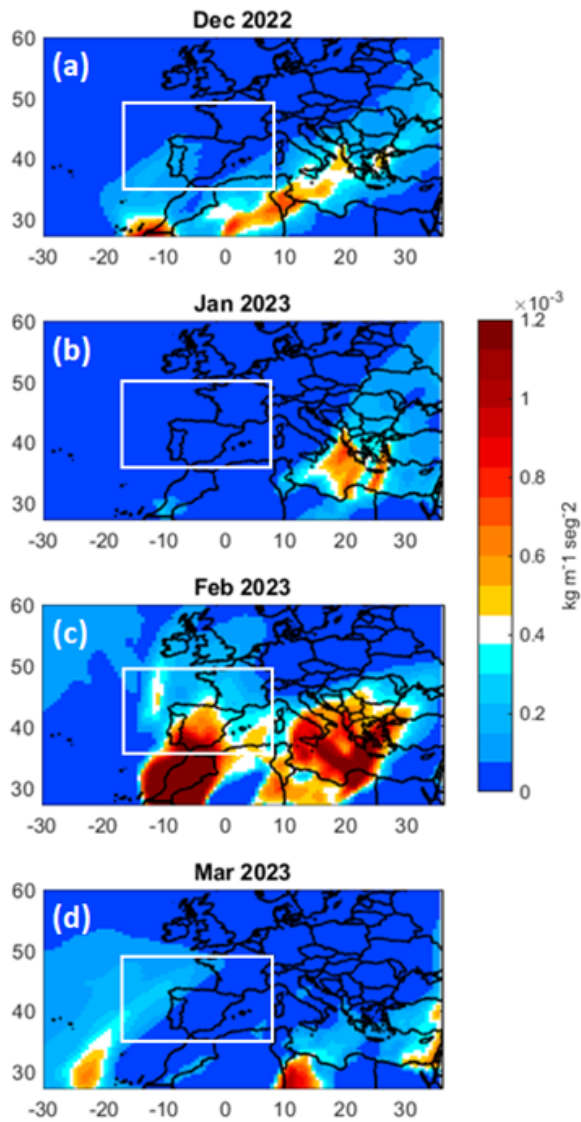
Palma de Mallorca	26/03/2013 – 28/03/2022	-0.002	0.48
Toulouse MF	10/03/2014 – 31/03/2022	+0.043	0.41

175

S3. Dust intrusions in winter 2022-2023

180

A preliminary analysis of dust intrusions in winter 2022-2023 can be summarised in Figures S12 and S13. The results show a peak in February 2023 associated to a particular event that affected the Iberian Peninsula. February 2023 is also observed a maximum in Sea Surface Temperature (SST) as it is shown in the time series of averaged region-monthly mean for each winter month (i.e., January, February and March) and the 2003-2023 period in the region that covers the easternmost part of the subtropical North Atlantic Ocean, and the westernmost Mediterranean (Alborán Sea and Balearic Islands) [30-40°N, 15°W-5°] is shown in Figure S14.



185

Figure S12: Averaged dust column V-wind mass flux (DUPLUXV; $\text{kg m}^{-1} \text{s}^{-1}$) for (a) December 2022, and (b) January, (c) February and (d) March 2023. Rectangle with a white perimeter (35°N-50°N, 20°W-5°E) marks the study area of dust intrusions towards Europe in the most western Mediterranean and the eastern North Atlantic around the Iberian Peninsula. Results based on based MERRA-2 reanalysis.

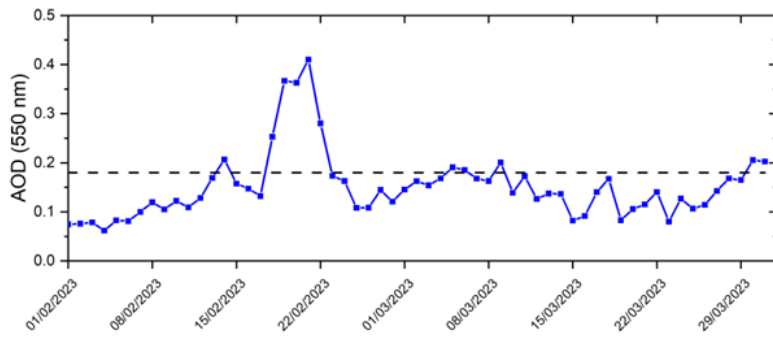


Figure S13: Daily averaged AOD within our study region [35-50°N, 20°W-5°E], from February 1st to March 31, 2023. Results based on MODIS aerosol retrievals (see Section 2).

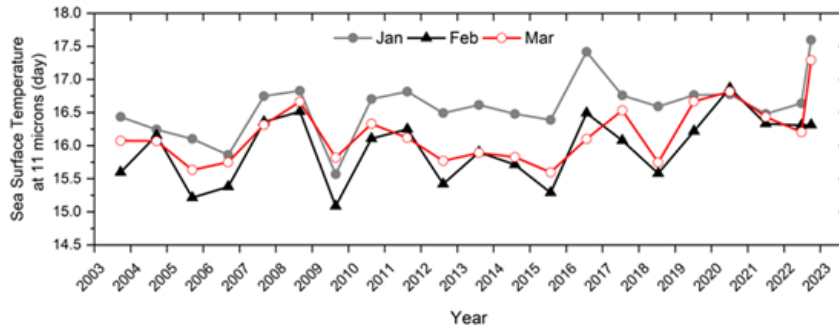


Figure S14: Time series of averaged region-monthly mean for each winter month (i.e., January, February and March) and the 2003-2023 period of the Sea Surface Temperature (SST) in the region that covers the easternmost part of the subtropical North Atlantic Ocean, and the westernmost Mediterranean (Alborán Sea and Balearic Islands) [30-40°N, 15°W-5°]. Results based on MODIS Water Reservoir Monthly L3 Global product (<https://modis.gsfc.nasa.gov/data/dataproduct/mod28.php>).