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*Interactive comment on "Sharp increase of Saharan dust intrusions over the Western Mediterranean and Euro-Atlantic region in winters 2020–2022 and associated atmospheric circulation.***" by Emilio Cuevas-Agulló et al.***

We are grateful for the positive evaluation and constructive comments, which have helped improve the manuscript. Our replies are shown below in blue, after the Reviewer's comments (in black).

Reply to Reviewer #2

1. The current study examines the meteorological drivers favored the occurrence of dust outbreaks in the western Mediterranean during winter periods over recent years (2020-2022). In winter, the occurrence of dust episodes is more common in the central/eastern Mediterranean in contrast to the western sector. The authors analyze/present a variety of reanalysis and observational datasets (observational, reanalysis) towards reaching to their goal. I have some concerns about the datasets which are utilized. Despite this, I believe that it is very interesting and constructive study, and it can be accepted for publication after revising the manuscript based on the following comments/suggestions:

Please, be aware that following the recommendation of one of the reviewers of the present manuscript the title is modified as *"Sharp increase of Saharan dust intrusions over the western Euro-Mediterranean in February-March 2020-2022 and associated atmospheric circulation".*

2. Page 6 – Line 12: Why are you using the MODIS Collection 6 data and not those of 6.1?

Thanks for noting the typo. We have used the MYD08_D3 v6.1 product, i.e. the level-3 MODIS gridded atmosphere daily global joint product (Collection 6.1). This has been corrected in the revised manuscript, including the following information in Section 2.1:

"We have used the NASA MODIS/Aqua daily global aerosol product (Collection 6.1), specifically, the AOD (at 550 nm) Combined for Land and Ocean product (Sayer et al., 2013), available since 2003 at 1º x 1º horizontal resolution."

3. Page 6 (Line 24) – Page 7 (Line 5): It would be useful here to elaborate how much your results are affected by "mixing" two different CALIPSO versions. I would remove Level

2.5km from the text because it is confusing (Level 2 – 5 km resolution along the satellite track).

Data generation and distribution of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Lidar Level 2 Vertical Feature Mask (VFM) is done through the NASA Atmospheric Science Data (ASC; https://asdc.larc.nasa.gov/project/CALIPSO). CALIPSO Level 2 VFM products has associated different versions. By the time in which the results of the manuscript were prepared, the only dataset covering most of the period was the CALIPSO VFM v3.x (2007-2021) and the 2022 was only available in v4.2. As it is shown in the comparison between the two CALIPSO versions (https://www-calipso.larc.nasa.gov/resources/calipso_users_guide/qs/cal_lid_l2_all_v4-20.php), the dust aerosol typing remains consistent. Noted that only recently (in December 2023), NASA ASC published a new CALIPSO Level VFM v4.5 (i.e. CAL_LID_L2_VFM-Standard-V4-51_V4-51) that is covering 2007-2022. Unfortunately, because the short notice, we are not in time to include this dataset in the revised manuscript. However, no substantial changes are considered in this v4.5 with respect to v3.x or v4.21 for the dust typing (see https://www-calipso.larc.nasa.gov/resources/calipso_users_guide/qs/cal_lid_l2_all_v4-51_qs.php). Then, we expect comparable results. In fact, a visual inspection of the results of the three CALIPSO Level 2 VFM versions for the dust episodes occurred in 2021 (http://www-calipso.larc.nasa.gov/about/) confirm it.

Following the Reviewer #2's suggestion, the description of the CALIOP products is revised as follows in Section 2.1 of the revised manuscript:

"Here, we use the available CALIPSO Lidar Level 2 VFM product from NASA Atmospheric Science Data Center, which includes Version 4.2 (2007-2021) and Version 3.1 (for year 2022). Please, note that these are the available CALIPSO datasets in the NASA Atmospheric Science Data (https://asdc.larc.nasa.gov/project/CALIPSO, last access 15 June 2023) by the time the results were processed. Despite the use of two different processing algorithms, the comparison between the two versions shows dust typing remains consistent (https://www-calipso.larc.nasa.gov/resources/calipso_users_guide/qs/cal_lid_l2_all_v4-20.php, last access 15 September 2023)."

4. Section 2.2: Can you explain why you are not using a more updated reanalysis dataset providing numerical products at finer spatial resolution (e.g., ERA5, GDAS)? I think that this is a very important issue since atmospheric patterns (not evident in the coarse NCEP/NCAR reanalysis dataset) can be revealed.

In this study we deal with synoptic and large-scale atmospheric circulation patterns. At these spatial scales global reanalyses provide similar patterns over the Euro-Atlantic sector. This is also true for the weather systems addressed in the manuscript, including blocking (see an inter-reanalysis comparison in Woollings et al., 2018) and the jet stream (see e.g. Barriopedro et al., 2023). We have repeated some of the analysis with ERA5 (see for example Figure R2.1), obtaining almost identical results. This has been stressed in the revised manuscript:

"the results of the atmospheric circulation analyses are robust to the study period (e.g. the 2003-2022 dust period) and the atmospheric reanalysis employed (e.g. ERA5; Hersbach et al., 2020)".

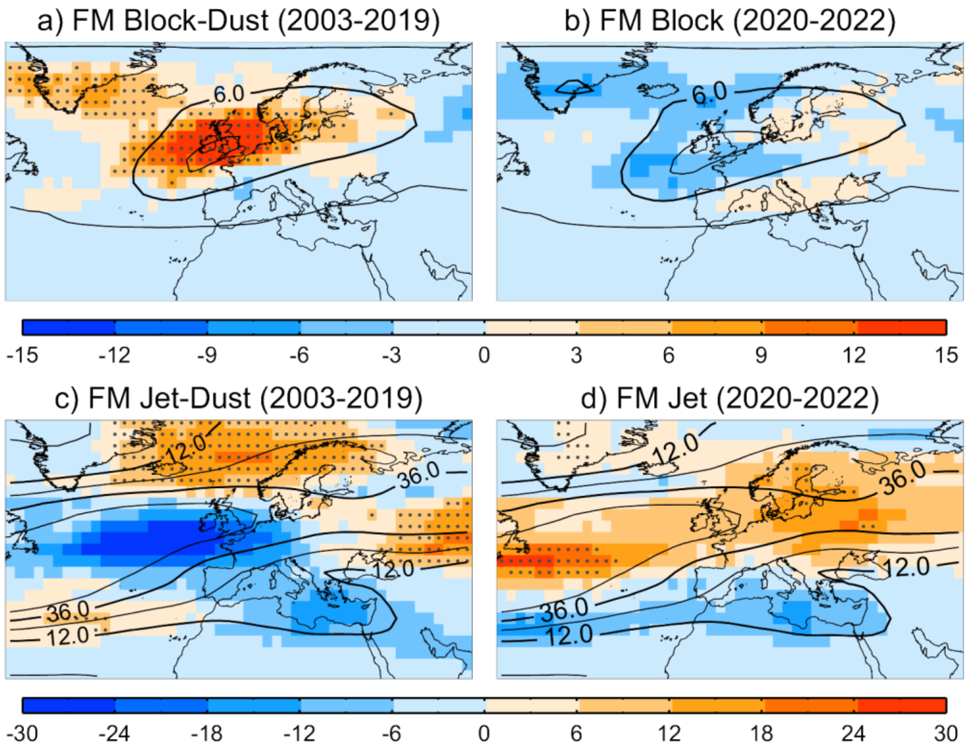

Figure R2.1. As Figure 6 of the main text but for ERA5.

5. Page 7 – Lines 18-19: Can you rephrase this sentence? It is not so clear.

The sentence has been revised in Section 3.1 of the revised manuscript as follows:

"A day is assigned to a given WR if the respective index is greater than 1 and higher than that of all other WRs".

6. Page 8 – Lines 11-12: Do you mean the low-level jet or there is mistake in the pressure levels?

The eddy-driven jet stream has been diagnosed with zonal wind data averaged between 925 and 700 hPa. This is a standard procedure and hence we have not modified the text. Zonal wind averages over the low-troposphere are often employed to emphasise the eddy-driven jet (which has a barotropic structure through the troposphere) and avoid the detection of the subtropical jet, which peaks in intensity in the upper troposphere (see e.g. Woollings et al. 2010 and references therein). Differently, the diagnosis of low-level jets requires finer information about the two wind components and the vertical structure of the wind in the lower troposphere (e.g. Bonner, 1986). Note that low-level jets, if present, would be filtered out in our approach by the spatio-temporal averages of the zonal wind.

7. Page 12 – Lines 1-16: The authors state that they are processing the MODIS L3 AOD data. Which data are used exactly (daily or monthly)? Can you comment (show) how cloud contamination can "impact" your results considering that the analysis is representative for winter months? Have you checked the temporal availability of the MODIS data? I assume that due to extended cloud coverage there will be gaps throughout the study period. If so, this might have impact on the calculation of the mean and standard deviation values.

For the analysis, it is considered the NASA MODIS/Aqua global daily AOD at 550nm Combined Land and Ocean product (Sayer et al., 2013), available since 2003 at 1º x 1º horizontal resolution (i.e. MYD08_D3). This is detailed in the revised manuscript. It is well-known that wintertime is the period of maximum rainfall and cloud cover in the region, and this affects remote sensing retrievals (e.g. Basart et al., 2009; Gkikas et al., 2016). Because MODIS can provide limited coverage during wintertime in the study region because of the presence of clouds (see Gkikas et al., 2016; Basart et al., 2009), MERRA-2 reanalysis dust product (which provides representative and complete dust fields in space and time) is used to support the results obtained with MODIS about the anomaly of events identified in 2020-2022 with respect 2003-2019. This is described in Section 2 of the revised manuscript:

"the identification and characterisation of dust events (Section 2.1) relies on satellite-based MODIS aerosol products over the available period of observations (2003-2022). Because of the limitations associated with satellite-based products to capture the daily cycle (i.e. satellite overpasses or cloud contamination), the analysis of dust events has also been done with the MERRA-2 global reanalysis (Randles et al., 2017), confirming the exceptional dust activity of the 2020-2022 period obtained from MODIS (Section S1 of the Supplement)."

8. Page 13 – Lines 4-17: It would be useful to discuss further the maximum occurrences recorded in February 2016 and 2017. How much different was the atmospheric circulation in the aforementioned months? Are they other factors which can explain these maximum frequencies?

Precisely the dust event of February 20-24, 2017 is analysed in detail in Section S1 of the Supplement as the first case study of the three dust events labelled as extreme. These results are shown in S1 of the submitted version of the Supplement.

Below (Figure R2.2) we include information on the atmospheric circulation corresponding to the dust event of February 29-24, 2017, which is compared with that of February 21-23, 2016.

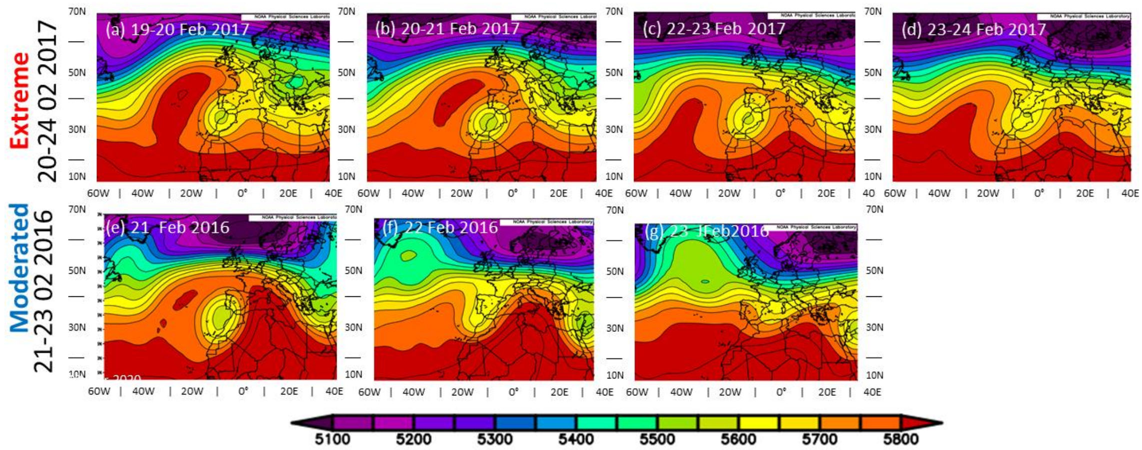

Figure R2.2 NCEP reanalysis mean Z500 for each day or subperiods of days for the two following dust events: February, 20-24, 2017 ((a), (b), (c) and (d)) and February, 21-23, 2016 ((e), (f), and (g)).

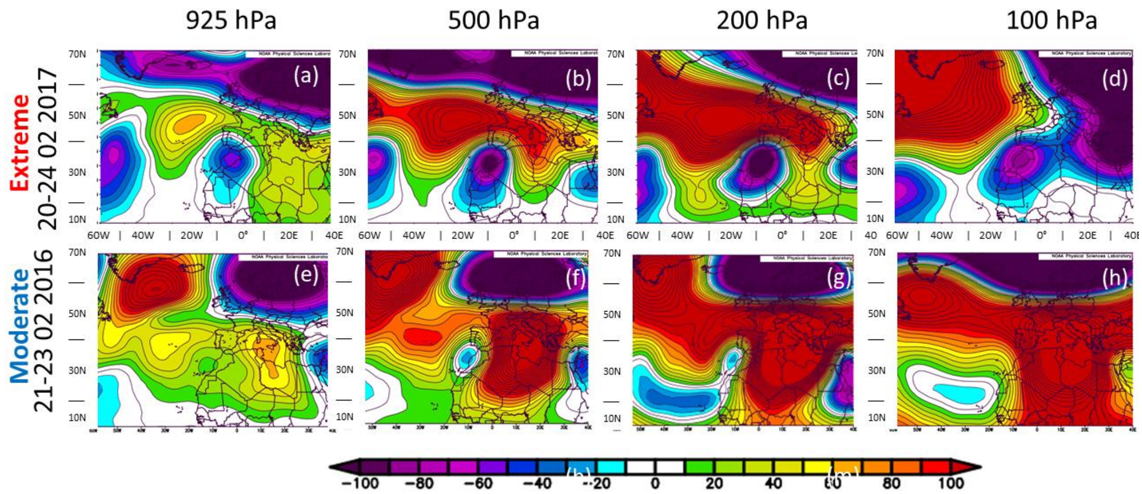

Figure R2.3. NCEP-Reanalysis geopotential height (Z) anomalies (m) at 925 hPa ((a) and (e), 500 hPa ((b), and (f)), 200 hPa ((c), and (g)), and 100 hPa ((d), and (h)), with respect to the reference period 1991-2020, for the following dust events occurred in the western Euro-Mediterranean. February 20-24, 2017; and February 21-23, 2016. Note that Z anomalies at each level, for brevity, have been averaged over the duration of each dust event (at least 3 three days).

Like the other case analyses, the February 21-23 ,2016 event shows a cut-off low to the west of the Atlas Mountains with very weak signal at 925hPa, and a downstream subtropical ridge, confirming the large-scale atmospheric patterns found in this study

9. Page 16 – Lines 13-14: How much different are the atmospheric patterns presented here with those discussed in previous relevant studies?

As far as we know, previous studies have not addressed in a systematic way the synoptic patterns (in particular, cut-off lows) associated with dust intrusions over western Mediterranean in February-March. We stated in the main text that: *"Winter dust intrusions over the western Mediterranean have received little attention and existing studies on the associated atmospheric circulation have mainly focused on synoptic systems during individual case studies."*

The two articles referenced in the text (Fernández et al., 2019; Oduber et al., 2019) did not describe the atmospheric process causing the dust events, since they focused on the optical characterization of dust and its impact in non-African regions. On the other hand, Francis et al. (2022) attributed the dust event included in our study (March 15-30, 2022) to the presence of a cut-off low located between the Canary Islands and the Iberian Peninsula.

As the Referee #2's statement refers to three dust events only, in Section 3 of the revised manuscript we have clarified that the results of these case studies should not generalised: *"Although these results should not be generalised to all dust events, the inspection of case studies suggests that cut-off lows and downstream high-pressure systems are commonly involved during WEM dust events."*

10. Page 16 – Lines 14-17: I would propose to rephrase these sentences to be consistent with the relevant figures. What do you mean four concatenated cut-off lows? How are you excluding the possibility of a persistent low-pressure system? I would suggest discussing more the position and the strength of the anticyclones as well as the convergence zones.

The identification of cut-off lows was carried out by visual inspection, following the conceptual model of Nieto et al. (2005). As stated in the text, these structures reach their maximum expression in the upper troposphere and the distinctive upper-level low does not often reach the surface. The absence of a surface low is the main difference between cut-off lows and extratropical cyclones. By "concatenated" cut-off lows we mean a clustering of cut-off lows (i.e. a sequence of multiple cut-off lows following similar paths). For each dust event, the identification of cut-off lows was determined by using 6-hourly fields of geopotential height and animated 15-min EUMETSAT RGB dust images. This can be seen in the three timelapses corresponding to the three extreme dust events that have been our three case studies (see the associated timelapses videos at https://repositorio.aemet.es/handle/20.500.11765/15054).

According to the Reviewer #2's suggestion, we have rephrased the corresponding sentences in the revised manuscript:

"In most cases, cut-off lows moved eastward from the subtropical North Atlantic to the western Mediterranean (see, e.g. the cut-off low to the west of the Atlas Mountains during the events of 20-24 February 2017 and 27-31 March 2021; Section S1 of the Supplement). The same event can comprise two or more successive cut-off lows. This situation was identified in at least one-third of the 2003-2019 dust events, but in almost all March dust events of the 2020-2022 period (see the sequence of cut-off lows over the coasts of Morocco and Algeria in the 15-31 March 2022 event; Section S1 of the Supplement)".

11. Page 17 – Lines 4-5: Can you please rephrase this sentence?

Thanks for noting. The sentence has been rephrased in the revised manuscript as follows:

"*Figure 4 shows the two most recurrent Z500 anomaly patterns obtained from the k-means clustering of FM dust days for the 2003-2019 and 2020-2022 periods".*

12. Figure 4: It seems that between the clusters 1 and 2 many similarities in spatial terms exist and there are deviations on the relative frequencies. Nevertheless, this is not the case for the clusters 3 and 4, as already stated in the manuscript. Can you please interpret the observed inconsistencies?

Figure 4 and the associated text have been modified in the revised manuscript following the recommendations of Reviewer #2. We have only defined two clusters, which yields a robust partitioning of the data while still retaining the major features of the dominant patterns associated with dust events (see Figure R2.2). This has been stated in Sections 2.2 and 3.2. of the revised manuscript:

"The selected number of clusters was limited to two, considering the relatively low number of dust days, particularly for the recent period of 2020-2022. The method assigns each dust day to

one of the two clusters, allowing us to explore the two main Z500 patterns associated with WEM dust intrusions"

[...]"we have only retained two clusters, which yields a robust partitioning of the data while still retaining the major features of the dominant patterns associated with dust events".

New cluster #1 shows similar spatial patterns in the two periods, and is more frequent in the anomalous period, whereas the spatial patterns of cluster #2 differ between the two periods. This suggest that blocking (cluster #1) is a recurrent driver of dust intrusions, being present in both the reference and anomalous period. Differences between clusters #2 suggest that other favourable atmospheric patterns (e.g. cut-off lows and subtropical ridges) occurred in the anomalous period, and with higher frequency than in the reference period. Therefore, the enhanced dust activity of the recent 2020-2022 period can partially be explained by a high frequency of recurrent (blocking) and less common (subtropical ridges) favourable patterns. The former (latter) was particularly prominent in March (February) 2020-2022.

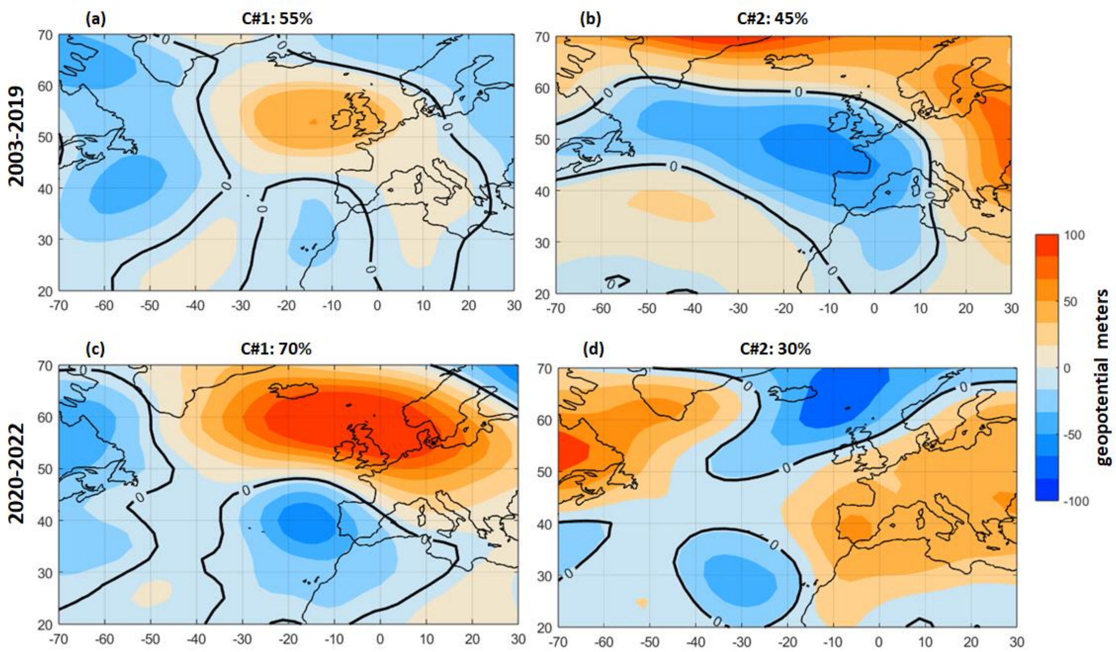

Figure R2.2 (new Figure 4). Two clusters (C#1 and C#2) of Z500 anomalies (in m) for the FM dust days of the normal-dust 2003-2019 (a-b) and the anomalous-dust 2020-2022 (c-d) period. The relative frequency of each cluster (in % with respect to the total number of dust days of each period) is indicated on the top.

13. Figure 5 and the relevant discussion: The authors state that "…that some WRs do not have a direct apparent correspondence with the clusters of Figure 4 (e.g., GL, ZO).". I am confused with this part of the study. How much can affect this inconsistency the connection between the patterns that you have obtained from the cluster analysis and the weather regimes of Grams et al. (2017)? If I am not missing something, in the latter study it is not considered the dust transport from N. Africa towards the region of interest.

These two analyses are complementary. The cluster analysis (Figure 4) addresses the atmospheric patterns responsible for dust intrusions, allowing us to discriminate multiple flow configurations leading to dust events. In this procedure, the focus is on dust events since we only consider dust days. The so-identified configurations do not necessarily match with recurrent synoptic patterns responsible for the day-to-day variability of the extratropical circulation. This assessment is provided by the weather regime (WR) analysis (Figure 5), which uses all days of the analysed period for the definition of WR. WRs allow us to infer if dust can occur preferentially under specific large-scale preferred patterns. This has been clarified in Section 2.2 of the revised manuscript as follows:

"First, we have carried out a characterisation of the synoptic patterns associated with dust events in order to discriminate different flow configurations leading to dust events" (…) *"To categorise the large-scale atmospheric circulation in a limited number of recurrent weather regimes (WRs) we have followed Grams et al. (2017), which uses an extended year-round classification of the Euro-Atlantic atmospheric circulation in seven WRs"*

One should not expect a perfect correspondence between the drivers (clusters) and favourable recurrent patterns (WRs) because 1) dust events are relatively uncommon (much less common than WRs), and 2) our clustering analysis indicates that there are several large-scale drivers of dust. As stated by the reviewer, the definition of WRs does not consider dust events only (as the clustering does). Despite this, we find a connection between both approaches. In particular, dust events tend to occur during WRs featuring high-pressure systems at different latitudes (i.e. European Blocking, EuBl; and Atlantic Ridge, AR), which is confirmed by the clustering analysis (cluster #2). The ZO pattern is also consistent with some circulation features of cluster #1, particularly one of the reference periods (Figure 4a). Therefore, the two approaches are consistent, which adds robustness to the analysis. We have revised the text Section 3.2 accordingly in the revised manuscript, including the following:

“The dust-related configurations identified in Figure 4 do not necessarily match with the dominant large-scale patterns responsible for the day-to-day variability of the extratropical circulation (WRs)”

“We note that none of the WRs coincide exactly with the dust-related patterns of Figure 4, *which is reflected in the dispersion of dust days across different WRs. As such, dust intrusions can occur under different WRs, stressing again the multiplicity of large-scale patterns compatible with dust events”*

“Therefore, dust intrusions can occur during WRs featuring high-pressure systems at different latitudes (mainly European Blocking, EuBl, and Atlantic Ridge, AR), which is consistent with the clustering analysis”.

14. Page 20 – Lines 1-4: It would be easy to reproduce the maps with winds at 10 meters in order to check in which regions the wind speeds exceed the thresholds.

We agree with the Referee #2. Figure R2.3 is included in the Supplement and referred in Section 3 of the revised manuscript.

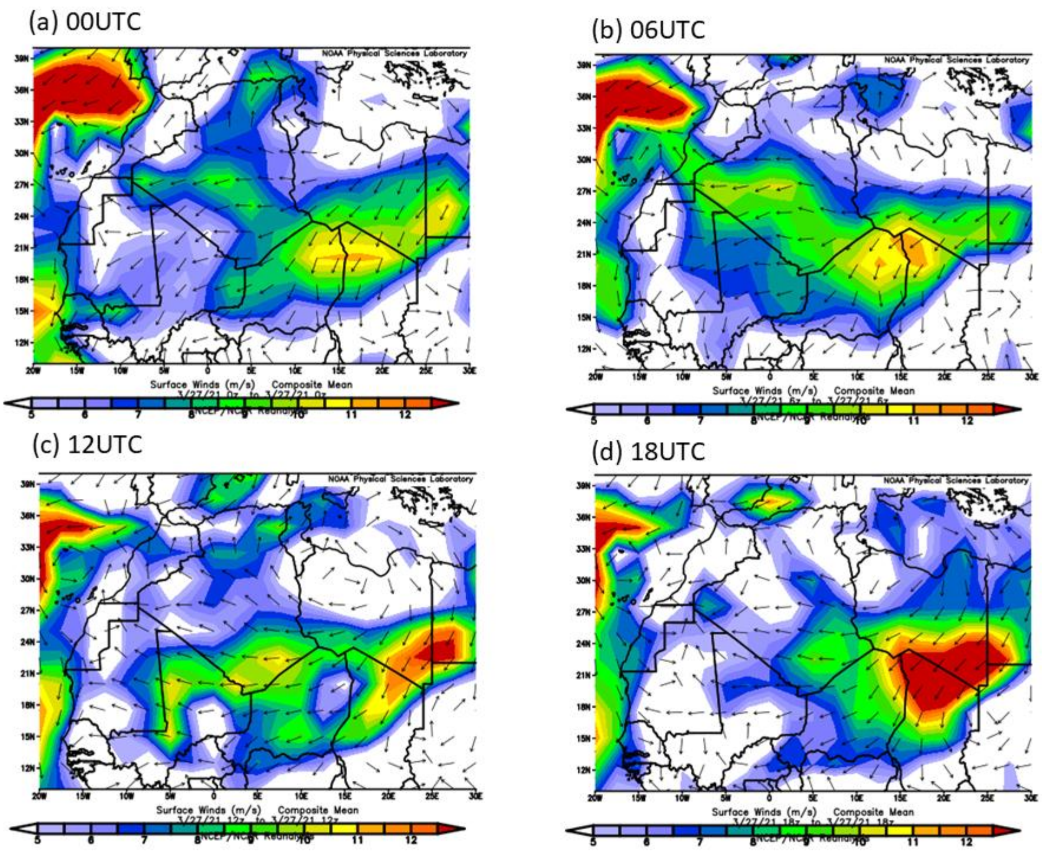

Figure R2.3 (Figure S15 added in the Supplement of the revised manuscript). NCEP Reanalysis vector wind for March 27, 2021: (a) 00 UTC; (b) 06 UTC; (c) 12 UTC; and (d) 18 UTC; Wind speed *scale ranges from 5 to 12.5 m·s^{-1} that is the range of wind speed threshold for dust mobilization in the west Sahara, which is between 5 and 12.5 m·s^{-1} (Helgren and Prospero, 1987).*

In the revised manuscript, we have added the following text after the sentence *"…they are intense enough to generate surface winds exceeding the wind speed threshold for dust mobilization in western Sahara, which is between 5 and 12.5 m·s-1 (Helgren and Prospero, 1987)*":

"This is supported by 6-hourly surface wind data from NCEP/NCAR reanalysis over Morocco, Algeria, Western Sahara and Mauritania (see Figure S15 of the Supplement)".

In addition, we have included, at the end of Section 2.1 of the revised manuscript the following lines:

"The identification of dust hotspots was performed using the EUMETSAT RGB dust product (Met Office; EUMETSAT, 2022). This dataset contains RGB dust images from Meteosat Second Generation satellites over the full disc at a frequency of 15 minutes".

In Section 3.2.2 of the revised manuscript is also added the following lines:

"*In the three case studies analysed, the geographical location as well as the activation time of each dust hotspot has also been identified manually (Schepanski et al. 2007, 2009, 2012) by using the 15-min EUMETSAT RGB dust animations (see timelapse videos at* ***https://repositorio.aemet.es/handle/20.500.11765/15054)***."

15. Page 20 – Lines 6-7: I would remove or rephrase the '…before being absorbed by the general circulation.'

Amended in the revised manuscript following the Referee #2's suggestion.

16. Section 4: Please consider splitting this section in "Discussion" and "Conclusions". Also, I believe that the part of the text after the bullets can be reduced by summarizing the main findings and outcomes.

Following the Referee #2's suggestion, the revised manuscript considers two sections. Also, the length of the text has been shortened, as suggested.

References

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