

Increase in probability of African dust outbreaks occurrence over Spain, driven by warming and changing atmospheric circulation patterns

Pedro Salvador

pedro.salvador@ciemat.es

CIEMAT

David Scofield

Pyrenean Institute of Ecology (IPE), CSIC

Noemí Pérez

CSIC

Andrés Alastuey

CSIC

Xavier Querol

CSIC

Manuel Pujadas

CIEMAT

Jorge Pey

Pyrenean Institute of Ecology (IPE), CSIC

Article

Keywords:

Posted Date: September 10th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10418183/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Increase in probability of African dust outbreaks occurrence over Spain, driven by warming and changing atmospheric circulation patterns

P. Salvador^{1*}, D. Scofield², N. Pérez³, A. Alastuey³, X. Querol³, M. Pujadas¹, J. Pey²

¹CIEMAT, Department of Environment, Air Pollution Unit 1, CIEMAT, Joint Research Unit with CSIC through IDAEA, Av. Complutense 40, 28040 Madrid.

²Pyrenean Institute of Ecology (IPE), CSIC, Av. Montañana 1005, 50059 Zaragoza.

³Institute of Environmental Assessment and Water Research (IDAEA), CSIC, c. Jordi Girona 18, 08034 Barcelona.

*Author to whom correspondence and material requests should be addressed. E-mail: pedro.salvador@ciemat.es

Author's ORCID iD:

Pedro Salvador: 0000-0002-0350-5296

David Scofield: 0009-0002-5786-6270

Noemí Pérez: 0000-0003-2420-6727

Andrés Alastuey: 0000-0002-5453-5495

Xavier Querol: 0000-0002-6549-9899

Manuel Pujadas: 0000-0002-5964-3962

Jorge Pey: 0000-0002-5015-1742

Abstract.

The main objective of this study is to estimate the contribution of thermodynamic and dynamic changes in the development of African Dust Outbreaks (ADO) over the western Mediterranean. To this end, values of daily probability of ADO occurrence over eight regions of the Iberian Peninsula and the Balearic Islands were calculated with numerical prediction models in 1940-2024. Then, a robust circulation classification methodology was applied to identify atmospheric circulation types favoring ADO. Finally, trend estimation and quantitative partitioning methods were also applied. Statistically significant increasing trends in days with a high probability of ADO occurring, defined as PROB-ADO extremes, were obtained in all zones. This resulted in a cumulative increase in PROB-ADO extremes in the range of 3–56 days/year, depending on the region. Statistically significant upward trends were also obtained for PROB-ADO extremes persistence in all regions, being more pronounced since 2000. Thermodynamic contributions to the PROB-ADO extreme trends were, in most cases, much greater (between 41% and 94%) than dynamic contributions (between 9% and 47%), suggesting an enhanced desert dust activity over the study regions. The intensification of high-pressure atmospheric systems over the Mediterranean and western Europe, sometimes reinforced by Atlantic low-pressure systems, were the main dynamic causes that contributed to the increase in the frequency and persistence of PROB-ADO extremes. Thus, the interaction between global warming effects and atmospheric circulation changes is yielding an increase in the transport of dust towards Spain over the last decades.

Introduction.

It is currently accepted that African dust is the main natural source contributing to increase regional PM₁₀ levels in southern Europe (Querol et al., 2009; Pey et al., 2013). It has also been shown that long-range transport processes of African dust known as African dust outbreaks (ADO) caused exceedances of the daily limit value for PM₁₀ for health protection (set at 50 µg/m³ in EU Directive 2008/50/EC on ambient air quality and a cleaner atmosphere in Europe (EC, 2008) and in the revised European Ambient Air Quality Directive (EU) 2024/2881 (EC, 2024)) at rural, suburban and urban air quality monitoring stations (Pey et al., 2013; Escudero et al., 2005; Salvador et al., 2013). The occurrence of ADO has also been associated with increased mortality and morbidity in southern European countries (Pérez et al., 2008; 2012; Stafoggia et al., 2016; Díaz et al., 2017). For this reason, the World Health Organisation Air Quality Guidelines have recognised the significant health risk posed by sand and dust storms in their latest update (WHO, 2021). In addition, ADO can also cause imbalances in the ecosystems of the western Mediterranean basin (Ridame et al., 2014; Pérez-Martínez et al., 2020).

Dust emissions from desert regions are highly sensitive to weather and climate conditions in the areas of origin (Goudie and Middleton, 2006). The gradual increase in temperatures and periods of drought throughout the 20th century, together with changes in land use, have increased the extent of desert areas in North Africa (Heffernan, 2016; Thomas and Nigam, 2018). This has led to greater mobilisation of dust particles as arid regions expand and vegetation cover decreases, favouring the development of dust storms (Ginoux et al., 2012; Zucca et al., 2021). As a result, significant interannual changes in the frequency of dust storms in the Sahara and Sahel regions have been detected during the second half of the 20th century (Prospero and Lamb, 2003; Prospero, 2006). Positive trends have also been identified in the development of ADO over areas of the Canary Islands (Alonso-Pérez, S. et al., 2011), central Europe (Varga, 2020) and the western Mediterranean basin (Salvador et al., 2022) over the last decades. Recent studies have also identified an increase in the 2020s in extreme ADO that have generated record PM₁₀ and PM_{2.5} values in different regions of Spain (Cuevas-Agulló et al., 2024; Rodríguez and López-Darias, 2024) as well as in areas of the central-eastern Mediterranean basin (Pons et al., 2025), especially between February and March.

Therefore, the apparent increase in the frequency and intensity of ADO in southern Europe detected in the last years could exacerbate the harmful effects on human health and ecosystems, which could even worsen in the coming years. For this reason, long-term assessment of African dust transport to these regions has become a necessity in order to diminish future impacts.

There is now strong evidence that anthropogenic climate change has altered the likelihood of extreme temperature and precipitation events in many regions of the planet. However, there is little or no consensus on its impact on ADO. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6, chapter 12) states that it has not been possible to find sufficient scientific literature to draw conclusions about the impact of global warming on sand and dust storms, although it acknowledges that these phenomena may be relevant in areas of the Mediterranean region (Masson-Delmotte et al., 2021).

In this regard, Salvador et al. (2024) developed a procedure for estimating the daily probability of ADO occurrence (PROB-ADO) over areas of the Iberian Peninsula (IP) and the Balearic Islands

(BI). In this study, it was demonstrated that exceeding successive threshold values for three thermodynamic variables (geopotential thickness in the 1000–500 hPa layer, GT; mean potential temperature between 925 and 700 hPa, TPOT; temperature anomalies at 850 hPa, TANOM) was associated with gradual increases in PROB-ADO over a long period of time (2001–2021 in this case). It allowed to develop multilinear regression models to calculate PROB-ADO using the daily mean values of GT, TPOT and TANOM as predictive parameters. Then, a statistically significant increase in the PROB-ADO was obtained for all regions of study over 1940–2021. This result suggested that the aggravation of warm conditions in southern Europe have modified the frequency of ADO over the western Mediterranean basin in the last decades.

However, the relative contributions of dynamic and thermodynamic factors to the observed increase in daily PROB-ADO remain unclear. This fact is not trivial, because the threshold values used to assign a specific PROB-ADO were defined on the basis of a list of actual events, identified for each study area over 2001–2021 using a robust and validated methodology. It must therefore be assumed that the PROB-ADO estimates obtained using this methodology also implicitly took dynamic factors into account.

As explicitly stated in the IPCC AR6 report in Chapter 11: "Changes in weather and climate extremes are determined by local exchanges in heat, moisture, and other related quantities (thermodynamic changes) and those associated with atmospheric and oceanic motions (dynamic changes). While thermodynamic and dynamic processes are interconnected, considering them separately helps to disentangle the roles of different processes contributing to changes in climate extremes" (Masson-Delmotte et al., 2021). In this respect, scientific literature has provided a growing body of evidence that anthropogenic climate change is not only causing large-scale thermodynamic changes, but is also affecting atmospheric circulation dynamics and, therefore, various types of extreme weather events (Horton et al., 2015; Mann et al., 2018; Jézéquel et al., 2018; Masson-Delmotte et al., 2021; Rogers et al., 2022; Faranda et al., 2023). The thermodynamic arguments are well understood and observed, but the dynamic arguments present greater uncertainties, highlighting the complexity of the issue (Shepherd, 2014; Cattiaux et al., 2016; Blackport and Screen, 2020; Riboldi et al., 2020; Martin, 2021; Martin and Norton, 2023).

In the case of ADO, it is well known that their seasonal and interannual variability of occurrence in the Mediterranean basin is related to the formation of certain atmospheric circulation types (CT). These CTs determine the source regions of desert dust, the areas affected by dust, and the time of year when these events will preferentially occur (Escudero et al., 2005; Querol et al., 2009; Pey et al., 2013; Salvador et al., 2014). Salvador et al. (2022) classified the 11 synoptic CTs that occurred most frequently at the 850 hPa level over areas of the European continent and North Africa over 1948–2020. Six of the 11 patterns were associated to a greater or lesser extent with the occurrence of ADO produced over several study areas of the IP-BI domain in 2001–2020 (ADO-CT). Each one had a varying impact in terms of dust load transported over each region and the season of the year when they preferentially occurred. The remaining patterns represent advections of air masses from different sectors of the Atlantic Ocean or the European continent, and were therefore not associated with the development of ADO over the study areas (nonADO-CT). Moreover, a statistically significant upward trend for days under ADO-CTs (0.77 days/year) was obtained along the period 1948–2020. This result suggests an increase in the frequency of

air masses being transported from North Africa to the western Mediterranean basin, in line with the findings regarding rising PROB-ADO trends.

With this information available in mind, the objective of this study is to estimate the contribution of global warming (thermodynamic factors) and of changes in ADO-CT and nonADO-CTs (dynamic factors) to the detected increase in the daily PROB-ADO in regions of the western Mediterranean basin.

To this end, ADO extreme occurrences were calculated using daily values of PROB-ADO at eight regions of the IP-BI domain (SE, SW, E, central, NE, N, and NW areas of the IP and the BI) over 1940-2024. Ad hoc statistical prediction models were made for each sub-domain for computing time series of PROB-ADO, using thermodynamic parameters (GT, TPOT and TANOM) as predictive variables (Salvador et al., 2024). PROB-ADO extremes were thus defined as days on which PROB-ADO exceeded the 90th percentile of the time series of daily values for the period 1940-2024. This is one of the most common approaches taken by the IPCC in its successive reports for characterizing extreme events (Masson-Delmotte, V. et al., 2021). Then, a circulation classification methodology was applied to group all days of the period 1940-2024 into one of the 11 characteristic CTs identified by Salvador et al. (2022). Next, temporal trends in the annual frequencies of the 11 CTs and of PROB-ADO extremes (days/year) were calculated for all study regions over 1940-2024. Finally, a quantitative partitioning method was applied to estimate the contributions of dynamic and thermodynamic factors to these trends.

In summary, this study aims to contribute to increasing knowledge about the complex interactions that occur in the atmosphere as a result of anthropogenic climate change and that give rise to extreme weather events with a high potential impact on humans and ecosystems, such as ADOs.

Results and discussion.

Time trends of PROB-ADO and PROB-ADO extremes occurrence and relationship with dust concentration parameters.

A number of studies have demonstrated that high values of GT, TPOT and TANOM define the presence of African air masses (warm, stable and dry air masses) over areas of the IP (Sánchez-Benitez et al., 2018; Sousa et al., 2019; Salvador et al., 2022). Several episodes were analysed in detail by Salvador et al. (2022; 2024), which demonstrated that maps of daily mean values of GT, TPOT and TANOM characterized very well the main thermodynamic features of intense ADO over the BI-IP domain. Namely, the location of the main pressure systems and the path followed by the dust plume. For this reason, they were selected as predictive parameters for computing PROB-ADO estimations (Salvador et al., 2024).

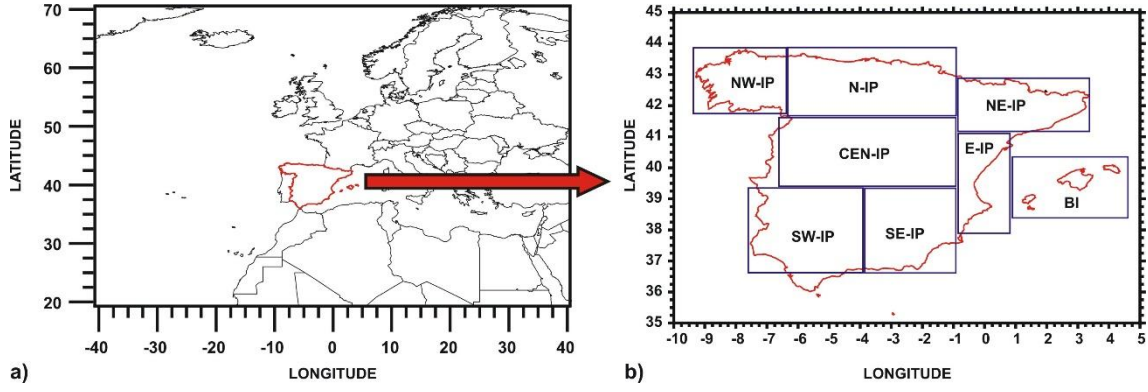


Figure 1. Geographical domain of the composite synoptic maps of geopotential height at 850 hPa at 12 UTC used to represent ADO and nonADO circulation types in the period 1940-2024 (a) and of the eight sub-domains in the Iberian Peninsula (IP) and the Balearic Islands (BI) (b).

Then, a comparison of GT, TPOT and TANOM time series, calculated from three different reanalysis data sets (“ERA5 hourly data on pressure levels from 1940 to present”, “NCEP/NCAR Reanalysis 1” and “NOAA-CIRES-DOE 20th Century Reanalysis V3”) was performed. Daily mean values of GT, TPOT and TANOM were calculated for each of the eight selected sub-domains of the IP-BI region (Figure 1) over the common period 1948-2015 to assess their similarity.

The values of the three thermodynamic parameters were highly consistent across the three reanalysis data sets. The Pearson correlation coefficients for the linear fits between pairs of values from the three reanalysis across each of the study areas, ranged from 0.919 to 0.974 for TANOM, from 0.979 to 0.991 for TPOT, and from 0.985 to 0.997 for GT (supplementary Table S1). Finally, the daily GH, TPOT, and TANOM data obtained from the reanalysis dataset with the highest spatial resolution, “ERA5 hourly data on pressure levels from 1940 to present”, were used to calculate PROB-ADO values with the numerical prediction models created for each study region following the procedure described in Salvador et al. (2024), (supplementary Figure S1). A threshold of 53% (90th percentile of the time series of daily PROB-ADO values) was thus determined for PROB-ADO extreme attribution.

Then, the occurrence of statistically significant upward trends in the PROB-ADO time series was confirmed across the period 1940–2024 in all the study regions. This increase was particularly evident since the 1970s (Figure 2). This trend behavior aligns with the important temperature increase detected in the Northern Hemisphere during the period 1976-2000, which was mostly attributed to anthropogenic causes (Marshall, 2001; Gillet et al., 2003; Masson-Delmotte et al., 2021).

With the aim to check the relationship between PROB-ADO estimates and the concentration of desert dust, daily mean values of net African dust regional contribution to PM₁₀ (PM_{10_net-dust}) and of 550 nm dust extinction aerosol optical thickness (AOT_{dust}) from MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2) were calculated for increasing ranges of values of PROB-ADO in the eight sub-domains over 2001-2024 (Figure 3).

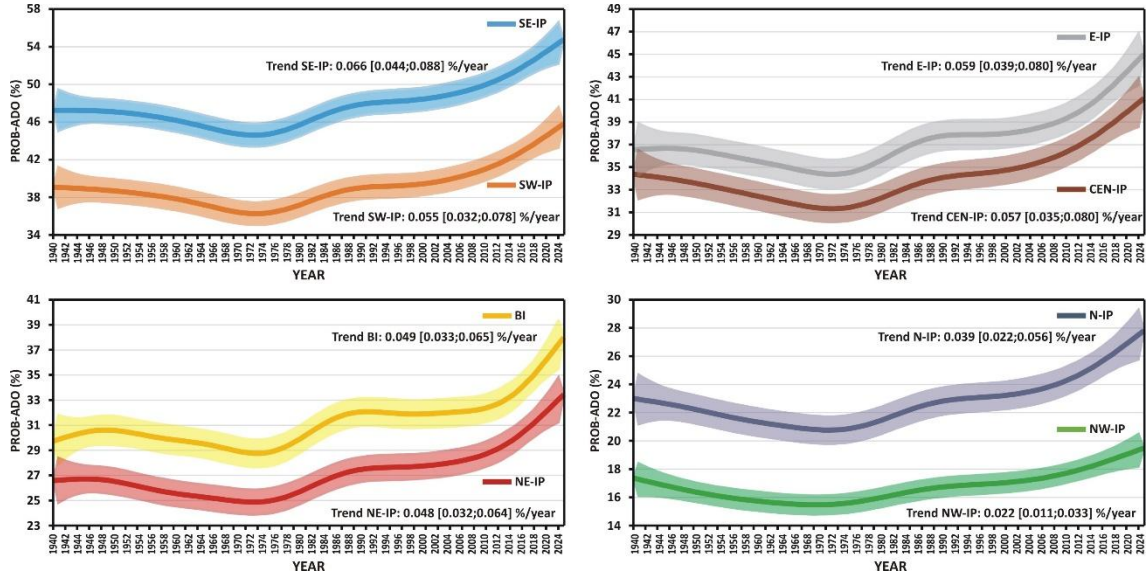


Figure 2. Smoothed trend and 95 % confidence intervals of the values of daily probability of occurrence of ADO (PROB-ADO) in the eight sub-domains of the Iberian Peninsula (IP) and the Balearic Islands (BI) for all days of the period 1940–2024. Values of the trend estimator and the 95 % confidence interval obtained with the Theil-Sen method are included in %/year.

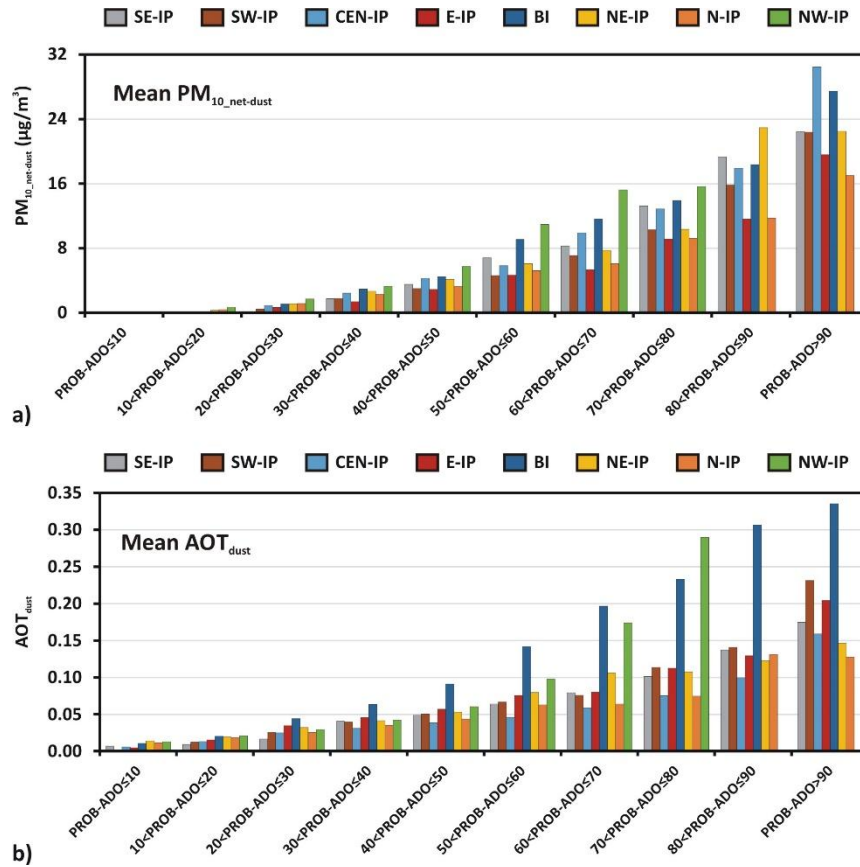


Figure 3. Daily mean values of $PM_{10_net-dust}$ (a) and AOT_{dust} (b) in 2001–2024 for increasing ranges of values of daily probability of occurrence of ADO (PROB-ADO) in the eight sub-domains of the Iberian Peninsula (IP) and the Balearic Islands (BI).

Although PROB-ADO values are based exclusively on parameters representing the thermodynamic characteristics of the air masses over the study areas, they showed a very good correlation with the concentration of desert dust at both high altitudes (AOT_{dust}) and at ground level ($PM_{10_net-dust}$) in these regions over 2001-2024 (Figure 3). The gradual increase in daily PROB-ADO values was associated with progressive increases in both AOT_{dust} and $PM_{10_net-dust}$ across all areas. Moreover, Figure 4 shows that during PROB-ADO extremes days, the medians of the time series of daily AOT_{dust} values for the grid points of each sub-domain were significantly higher than those for all days in the period 1980–2024.

These results support the hypothesis that there is a direct relationship between the thermodynamic characteristics of the air masses, which defines their origin over North African regions, and the load of desert dust transported by them. Thus, higher thermodynamic contributions to upward PROB-ADO trends can be interpreted as increased desert dust activity over these regions.

Then, the temporal trends in PROB-ADO extremes occurrence were estimated for the period 1940–2024. Statistically significant upward estimators were obtained in all zones. They represent the increase in the annual frequency of days on which PROB-ADO extremes occurred. Such increases ranged from 0.016 days/year in the NW-IP zone to 0.628 days/year in the SE-IP area (Figure 5a). There was a clear decreasing gradient along the SE-NW axis. These results indicate a cumulative increase from 1940 to 2024 of 2.7 days/year in the NW-IP region to 55.7 days/year in the SE-IP region during which PROB-ADO extremes were reached.

In addition, robust positive trends were determined for PROB-ADO extremes persistence in all study regions (Figure 6). In this context, persistence represents the duration in days of consecutive PROB-ADO extremes occurrence. Trend estimators were rather low, ranging from 0.004 days/year in the NW-IP region to 0.015 days/year in the SE-IP region. However, it is clear that in most regions, the rate of growth was more pronounced since the end of the 20th century (Figure 6). By limiting the trend calculation to the period 2000–2024, the trend estimates increased significantly to values in the range 0.026-0.098 days/year.

Classification of synoptic atmospheric circulation patterns during ADO.

The results of the circulation classification procedure with “ERA5 hourly data on pressure levels from 1940 to present”, “NCEP/NCAR Reanalysis 1” and “NOAA-CIRES-DOE 20th Century Reanalysis V3” 850 hPa geopotential height fields at 12 UTC have allowed identifying the 6 ADO-CTs (supplementary Figure S3) and the 5 nonADO-CTs (supplementary Figure S4) obtained in Salvador et al. (2022).

The intercomparison of the results, revealed that the three data sets agreed on the same CTs on 85% of the days within the common period 1948-2015.

The classification pattern of the days within this period across the 11 characteristic CTs was very similar (supplementary Figure S5). In all cases, the most frequent pattern was ADO-CT1, followed by ADO-CT6 and nonADO-CT5. Taken together, these accounted for between 33.2% and 36.3% of the days in the entire period. The least frequent pattern was nonADO-CT4, which accounted for between 5.8% and 6.5% of the days. The remaining patterns had a similar frequency of occurrence, ranging from 7.5% to 10.2% of the days in the period.

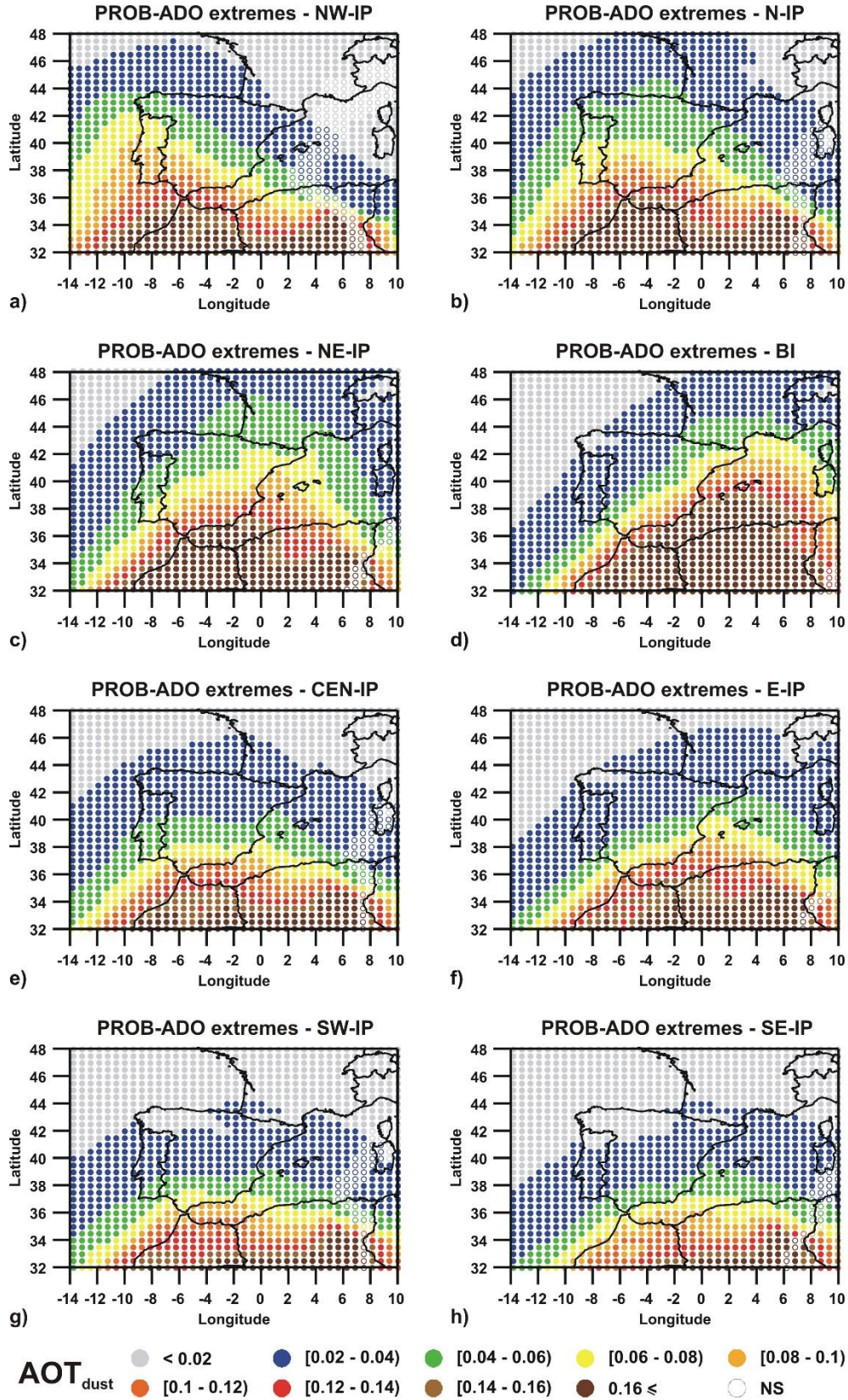


Figure 4. Medians of AOT_{dust} values for days of extreme probability of occurrence of ADO (PROB-ADO extremes) in the eight sub-domains of the Iberian Peninsula (IP) and the Balearic Islands (BI) in 1980-2024. White circles (NS) show medians, which were not significantly higher than the medians for all days of the period.

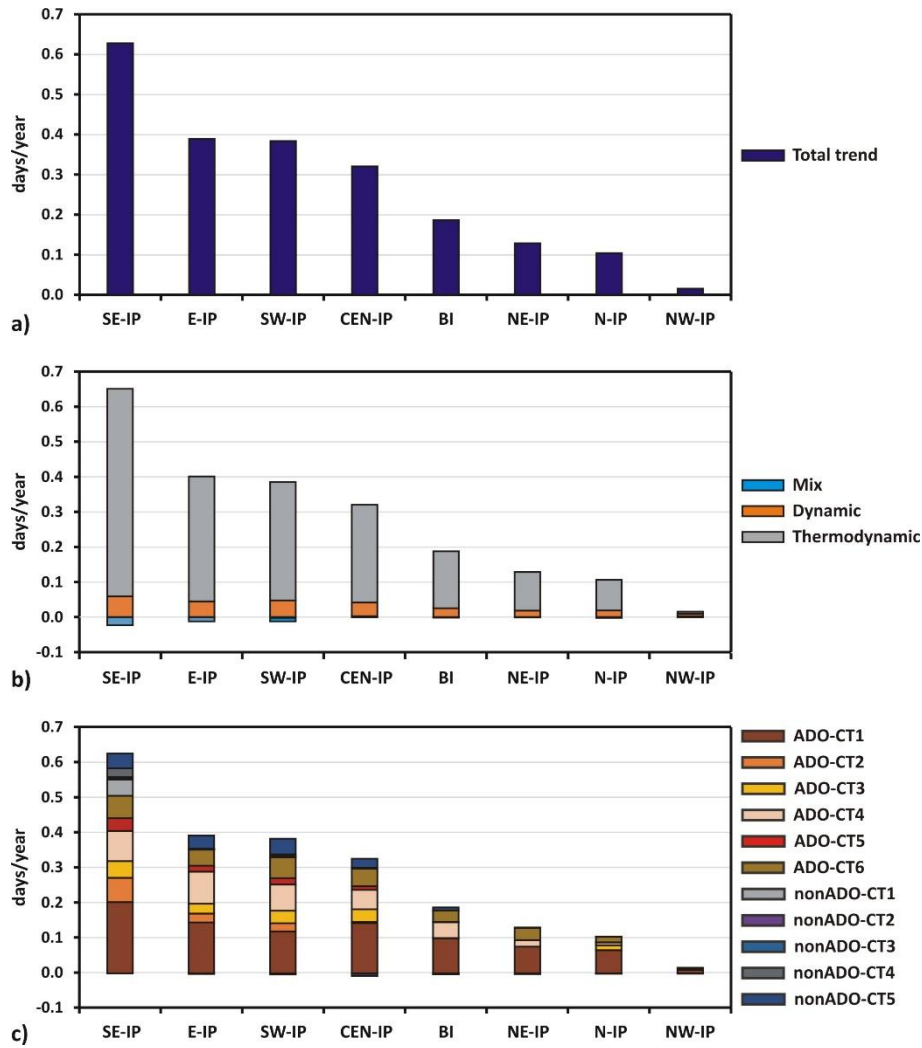


Figure 5. Overall (a) and disaggregated trends by cause (b) and circulation type (c) of PROB-ADO extremes occurrence (days/year) in the eight sub-domains of the Iberian Peninsula (IP) and the Balearic Islands (BI) for the period 1940-2024.

The seasonal variation was also very similar. In summer, the ADO-CT1, ADO-CT6 and nonADO-CT5 patterns prevailed; in winter, ADO-CT2, nonADO-CT1 and nonADO-CT4; in spring, nonADO-CT2; and in autumn, ADO-CT3, ADO-CT4 and ADO-CT5 (supplementary Figure S6).

Finally, trend estimators in the annual frequency of occurrence for each CT were calculated using the results of the classification procedure from the three reanalysis data sets over the common period 1948-2015 (supplementary Figure S7). No statistically significant differences were found in any CT between the trend estimators derived from the results of the three reanalysis datasets at the 95% confidence level. Moreover, trends of similar magnitude, sign and statistical significance were obtained. In most cases, statistically significant upward trends were determined for several ADO-CTs (ADO-CT1, ADO-CT2, ADO-CT4 and ADO-CT6) whereas decreasing trends arose for most nonADO-CTs (nonADO-CT2, nonADO-CT3, nonADO-CT4 and nonADO-CT5). The temporal evolution for the other CTs did not show any significant trend over 1948-2015.

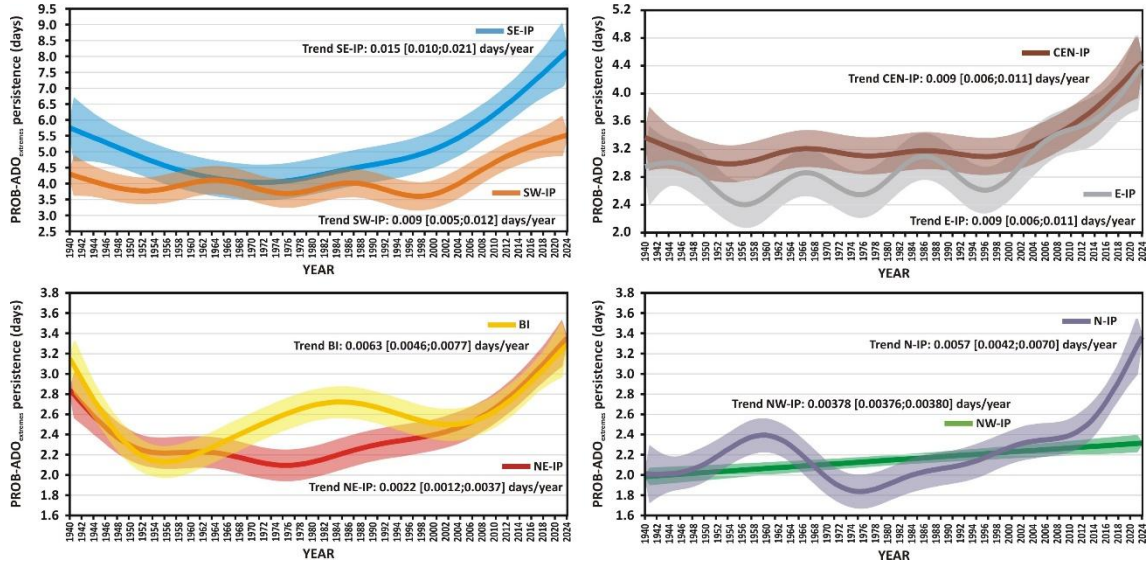


Figure 6. Smoothed trend and 95 % confidence intervals of the duration of consecutive days with extreme probability of ADO occurrence (PROB-ADO extremes persistence) in the eight sub-domains of the Iberian Peninsula (IP) and the Balearic Islands (BI) for all days of the period 1940–2024. Values of the trend estimator and the 95 % confidence interval obtained with the Theil-Sen method are included in days/year.

As a result of this comparative study, it can be assumed that the results of the CTs classification process obtained using ERA5 reanalysis data, as well as their seasonal and temporal evolution, are robust and reflect significant evidences of long-term changes in atmospheric circulation over the western Mediterranean and the North of Africa.

Finally, the values of the trend estimators for the period 1940–2024 from ERA5 reanalysis data fields were used for the quantitative partitioning of the contributions of each individual CT to the general trend in the occurrence of PROB-ADO extremes over each region of study (supplementary Figure S7).

Interpretation of the causes of the trends in the occurrence of PROB-ADO extremes.

Results of the quantitative partitioning of the thermodynamic, dynamic and mixed contributions to the trends in the occurrence of PROB-ADO extremes are showed in Figure 5b and Table 1.

Thermodynamic contributions were predominant, ranging from 41% in NW-IP to 94% in SE-IP. There was a clear decreasing gradient along the SE to NW axis. The dynamic contribution was smaller, ranging from 9% in SE-IP to 47% in NW-IP. Mixed contributions were very small, ranging from -4% to 1% in all regions but NW-IP, where it reach 12%. They were mostly negative, indicating that this type of interaction didn't contribute to an increase in the trend of PROB-ADO extremes.

The contributions to the overall trend in PROB-ADO extremes in each zone, resulting from the occurrence of different atmospheric CTs, were then assessed (Figure 5c and Table 1). The cumulative contribution of ADO-CTs ranged from 81% in SE-IP to 100% in N-IP and NE-IP.

Table 1. Quantitative partitioning of PROB-ADO extreme trends (% of the total) for specific causes, circulation types and regions of study.

	SE-IP	E-IP	SW-IP	CEN-IP	BI	NE-IP	N-IP	NW-IP
Trend estimator (days/year)	0.63	0.39	0.38	0.32	0.19	0.13	0.10	0.02
Causes								
Mix	-4%	-3%	-1%	1%	-1%	0%	-2%	12%
Dynamic	9%	11%	12%	12%	14%	14%	18%	47%
Thermodynamic	94%	92%	88%	87%	87%	86%	84%	41%
Total	100%	100%	100%	100%	100%	100%	100%	100%
Circulation Types								
ADO-CT1	32.4%	37.4%	31.2%	44.9%	53.9%	59.2%	63.7%	66.8%
ADO-CT2	11.0%	6.4%	6.1%	0.8%	-0.2%	0.3%	-0.5%	0.0%
ADO-CT3	7.6%	7.2%	9.3%	11.3%	0.1%	-0.5%	13.7%	-0.4%
ADO-CT4	13.7%	23.6%	19.4%	17.4%	24.4%	14.4%	7.5%	1.3%
ADO-CT5	5.9%	4.3%	4.9%	3.2%	0.2%	0.0%	0.1%	0.2%
ADO-CT6	10.2%	11.8%	15.5%	15.5%	17.8%	27.2%	15.4%	31.4%
nonADO-CT1	7.3%	0.2%	0.9%	0.8%	-0.1%	-0.1%	-0.1%	0.0%
nonADO-CT2	0.6%	0.1%	1.3%	-2.0%	-0.5%	0.1%	-0.2%	0.4%
nonADO-CT3	0.5%	-0.3%	0.3%	0.1%	-0.1%	0.0%	0.0%	0.0%
nonADO-CT4	4.0%	-0.5%	-0.5%	-0.3%	-0.2%	0.0%	0.0%	0.0%
nonADO-CT5	6.8%	9.6%	11.6%	8.2%	4.6%	-0.5%	0.4%	0.3%
Total	100%	100%	100%	100%	100%	100%	100%	100%
Causes & Circulation Types								
ADO-CT1 Mix	0.76%	0.05%	0.14%	1.15%	-0.49%	0.36%	0.73%	-2.36%
ADO-CT1 Dyn.	10.70%	9.18%	10.66%	9.33%	11.41%	10.61%	13.20%	39.95%
ADO-CT1 Ther.	20.97%	28.20%	20.45%	34.45%	43.02%	48.27%	49.79%	29.23%
ADO-CT2 Mix	-0.80%	-0.74%	-0.57%	-0.70%	-1.05%	-0.35%	-1.28%	-0.30%
ADO-CT2 Dyn.	3.98%	1.74%	2.25%	1.53%	0.83%	0.68%	0.83%	0.31%
ADO-CT2 Ther.	7.81%	5.45%	4.46%	0.00%	0.00%	0.00%	0.00%	0.00%
ADO-CT3 Mix	-0.68%	-0.72%	-1.12%	-1.50%	0.05%	-0.58%	-2.46%	-0.93%
ADO-CT3 Dyn.	0.18%	0.11%	0.17%	0.16%	0.08%	0.11%	0.19%	0.57%
ADO-CT3 Ther.	8.10%	7.81%	10.20%	12.63%	0.00%	0.00%	15.97%	0.00%
ADO-CT4 Mix	-0.39%	-0.98%	-0.61%	0.00%	-1.23%	-0.91%	1.05%	-0.11%
ADO-CT4 Dyn.	3.68%	3.21%	2.90%	2.44%	2.77%	1.84%	1.98%	1.39%
ADO-CT4 Ther.	10.40%	21.36%	17.13%	14.91%	22.90%	13.43%	4.48%	0.00%
ADO-CT5 Mix	0.46%	0.11%	0.13%	0.47%	0.12%	-0.10%	0.09%	0.00%
ADO-CT5 Dyn.	0.12%	0.07%	0.09%	0.07%	0.06%	0.05%	0.05%	0.24%
ADO-CT5 Ther.	5.28%	4.13%	4.64%	2.69%	0.00%	0.00%	0.00%	0.00%
ADO-CT6 Mix	0.00%	-0.29%	1.14%	0.97%	0.39%	0.85%	-1.11%	9.63%
ADO-CT6 Dyn.	2.63%	2.04%	3.28%	2.93%	2.09%	2.12%	3.06%	9.68%
ADO-CT6 Ther.	7.56%	10.03%	11.06%	11.61%	15.32%	24.19%	13.42%	12.04%
nonADO-CT1 Mix	-0.97%	-0.68%	-0.24%	0.22%	-0.22%	-0.32%	-0.35%	-0.20%
nonADO-CT1 Dyn.	2.85%	0.86%	1.15%	0.57%	0.15%	0.21%	0.25%	0.16%
nonADO-CT1 Ther.	5.46%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
nonADO-CT2 Mix	0.17%	0.00%	0.38%	0.03%	0.64%	0.58%	0.57%	2.73%
nonADO-CT2 Dyn.	-4.72%	-1.96%	-2.88%	-2.00%	-1.18%	-0.49%	-0.81%	-2.29%
nonADO-CT2 Ther.	5.12%	2.09%	3.76%	0.00%	0.00%	0.00%	0.00%	0.00%
nonADO-CT3 Mix	-2.03%	0.53%	0.66%	0.74%	0.90%	0.11%	0.00%	0.00%
nonADO-CT3 Dyn.	-4.98%	-1.57%	-1.63%	-0.68%	-0.96%	-0.10%	0.00%	0.00%
nonADO-CT3 Ther.	7.56%	0.78%	1.28%	0.00%	0.00%	0.00%	0.00%	0.00%
nonADO-CT4 Mix	-0.21%	-0.03%	0.07%	0.01%	0.08%	0.04%	0.00%	0.00%
nonADO-CT4 Dyn.	-1.60%	-0.42%	-0.54%	-0.27%	-0.26%	-0.06%	0.00%	0.00%
nonADO-CT4 Ther.	5.81%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
nonADO-CT5 Mix	0.00%	-0.36%	-0.51%	-0.59%	0.00%	0.26%	1.17%	3.56%
nonADO-CT5 Dyn.	-3.44%	-1.77%	-3.05%	-1.84%	-1.36%	-0.79%	-0.81%	-3.30%
nonADO-CT5 Ther.	10.21%	11.76%	15.14%	10.65%	5.96%	0.00%	0.00%	0.00%
Total	100%	100%	100%	100%	100%	100%	100%	100%

The largest overall contribution across the different regions came from the occurrence of the ADO-CT1 (between 31.2% in SW-IP and 66.8% in NW-IP of the trend, 48.7% on average) and, to a lesser extent, ADO-CT6 (between 10.2% in SE-IP and 31.4% in NW-IP of the trend, 18.0% on average) circulation patterns. The other ADO-CTs made a lesser mean contribution and were highly dependent on the geographical region. ADO-CT2 and ADO-CT5 contributed between 6.1% and 11.0% and between 4.3% and 5.9% to the overall trend, respectively, in areas of the southern third and the eastern region of the IP. ADO-CT4 contributed between 13.7% and 24.4% in areas of the southern half and the eastern sector of the IP-BI domain, and ADO-CT3 between 9.3% and 13.7% in SW-IP, CEN-IP and N-IP and 7.2% and 7.6% in E-IP and SE-IP, respectively.

NonADO-CTs didn't contribute substantially to the overall trend (below 1.0% in most sites), either because they didn't exhibit significant temporal trends or, even where they did, as in the case of nonADO-CT2 and nonADO-CT3 which recorded the highest decreasing trends, PROB-ADO extremes almost never occurred during days under these CTs. The development of nonADO-CT5, generated moderate positive contributions to the trends determined at the southern, central and eastern regions of the IP-BI domain (from 4.6% in BI to 11.6% in SW-IP). This CT was mostly generated in summer when more ADOs were registered.

It should be kept in mind that, although the synoptic weather conditions that triggered ADOs may have changed and the air masses of African origin no longer linger over the study areas, the dust transported at different altitudes may still take between 2 and 3 days to settle and dissipate (Commission Staff Working Paper, 2011). Consequently, they will still contribute to increased surface PM₁₀ levels due to desert dust contributions and are therefore classified as ADO episodic days. For this reason, a small percentage of the ADO episodic days are attributed to nonADO-CTs, mainly in summer when more ADOs were detected, and consequently they could have associated relatively high PROB-ADO values. This fact could explain the moderate contributions, mostly due to thermodynamic factors, obtained for several nonADO-CTs to the upward trends PROB-ADO extremes in some of the sub-domains.

Results of the quantitative partitioning analysis also revealed that thermodynamic contributions associated with specific CTs were higher than the dynamic contributions in most areas (Table 1). These thermodynamic contributions were particularly significant on days under the ADO-CT1, accounting for between 20.5% (in SW-IP) and 49.8% (in N-IP) of the total trend, and were below 25% for the remaining ADO-CTs. The development of nonADO-CTs typical of the warmest months, such as nonADO-CT5, has also generated positive thermodynamic contributions, although in most cases these didn't exceed 5% of the total trend.

Furthermore, between 9.2% (in E-IP) and 40.0% (in NW-IP) of the increasing trends in PROB-ADO extremes detected across the eight study regions could be attributed to the dynamic influence of the increased frequency of the ADO-CT1 pattern. Lower dynamic contribution of ADO-CT6 to PROB-ADO extremes trends has also been obtained in all regions, ranging from 2.0% in E-IP to 9.7% in NW-IP. The dynamic contributions to the overall trend in extreme PROB-ADO estimated for the remaining CTs have been smaller. They reach values in the range 2% – 4% on days under ADO-CT2 in SE-IP and SW-IP and under ADO-CT4 in SE-IP, E-IP, SW-IP, CEN-IP and BI and below 2% in the remaining areas and CTs. In fact, most of the dynamics contributions associated with nonADO-CTs were close to zero or even negative, as a result of the declining trends obtained in the occurrence of these CTs during the study period.

When attempting to analyse the factors underlying the dynamic contributions of ADO-CT1 and ADO-CT6 to the increasing PROB-ADO extremes trends, it is important to bear in mind that the transport of African air masses over the western Mediterranean generated by ADO-CT1 was caused by the presence of high-pressure systems over north-eastern Algeria, Tunisia and north-western Libya, as well as a low-pressure centre over Morocco (supplementary Figure S3a). ADO-CT6 is similar, although in this case the high-pressure systems were shifted towards northern Algeria and the IP, and the low-pressure centre was shallower (supplementary Figure S3f). This is why air masses with an S-SE component are advected over the IP-BI domain, mainly during the warmer months of the year. It has been observed that, as the PROB-ADO value increased progressively on days when extreme PROB-ADO events occurred, ADO-CT1 and ADO-CT6 evolved in the same way.

Figures 7 and 8 show this evolution in the BI, SW-IP and N-IP sub-domains for ADO-CT1 and ADO-CT6, respectively. Composites for all regions are contained in supplementary Figures S8 and S9. Firstly, a gradual increase in the intensity of the high-pressure system was observed. Afterwards, its position gradually shifted to higher altitudes, eventually generating a blocking anticyclone over western Europe. The same result was obtained on average across all study areas, although there were differences in the position of the anticyclone. It has tended to shift further eastwards over areas of the eastern third of the IP and the BI (Figures 7a and 8a) and further westwards on PROB-ADO extreme days over areas of the western sector of the IP (Figures 7b-c and 8b-c). It has also reached higher latitudes on PROB-ADO extreme days over NW-IP and N-IP (Figures 7c and 8c), the regions with higher dynamic contributions to the total trend. It seems clear that in regions furthest from the source of desert dust, dynamic factors have played a more decisive role than thermodynamic factors in generating PROB-ADO extremes over the western Mediterranean. In other words, for the dust to be transported to more distant regions, very intense CTs must occur, as shown in Figures 7c and 8c for the N-IP sub-domain.

Moreover, upward trends in PROB-ADO extremes persistence were determined under ADO-CT1 and ADO-CT6 in most regions (Table 2). Trend estimators for ADO-CT1 were statistically significant with at least a 95% confidence level in all regions but NW-IP and N-IP and ranged from 0.003 days/year in CEN-IP to 0.013 days/year in NE-IP. In the case of ADO-CT6, statistically significant trend estimates were also obtained in all regions except CEN-IP. These values were lower than those for ADO-CT1 and ranged from 0.0004 days/year in N-IP to 0.008 days/year in NW-IP. Statistically significant upward trends were also obtained in some sub-domains for other ADO-CTs, mainly ADO-CT4, but in many cases the trend estimators were negative or non-statistically significant.

In summary, the dynamic contributions to the overall upward trends in PROB-ADO extremes can be attributed not only to an intensification-amplification of circulation patterns ADO-CT1 and ADO-CT6 but also to an increase in their persistence in most sub-domains.

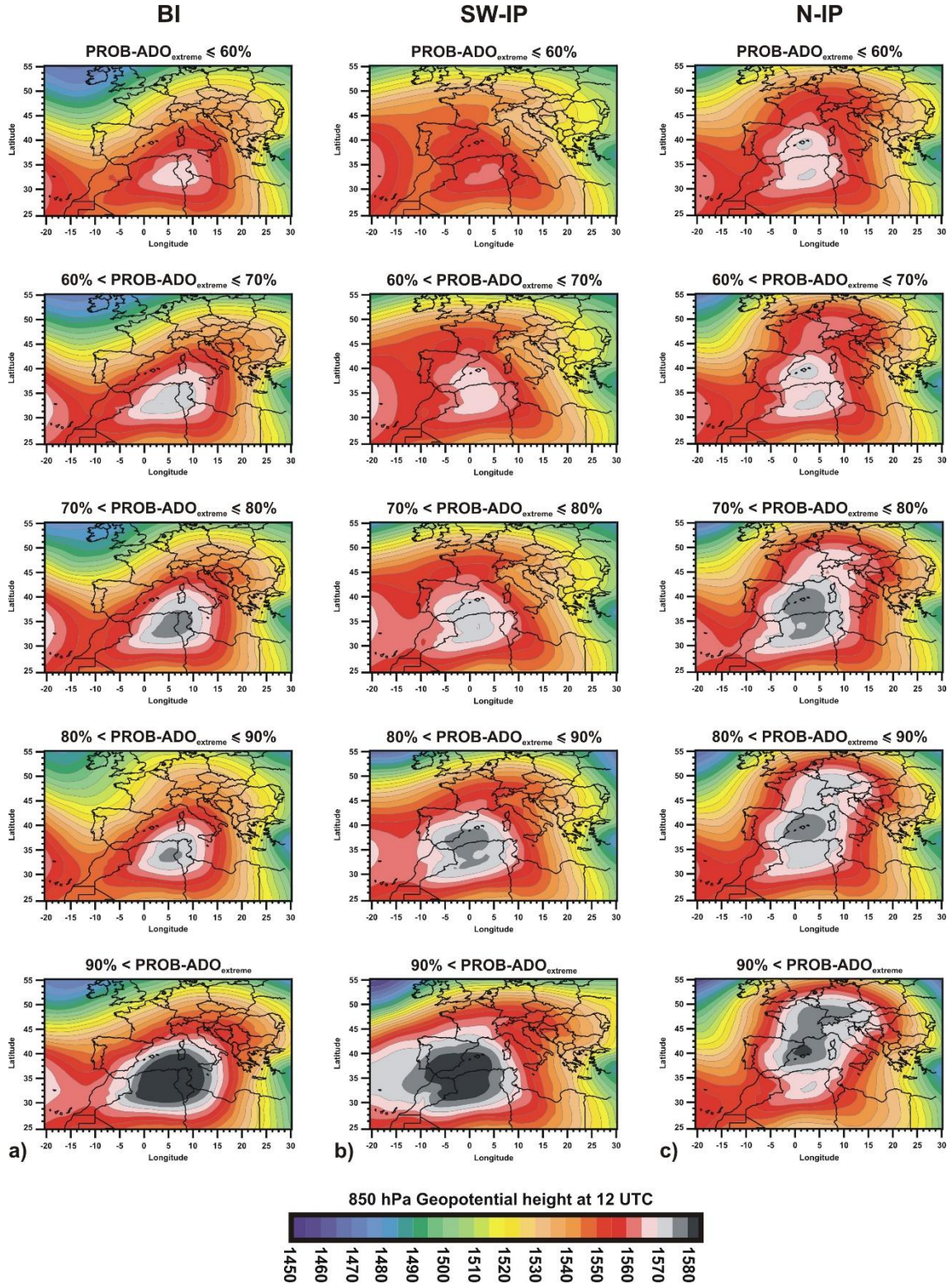


Figure 7. Composites of 850 hPa geopotential height at 12 UTC (in m) for increasing PROB-ADO extremes days under ADO-CT1 in the BI (a), SW-IP (b) and N-IP (c) sub-domains over 1940–2024.

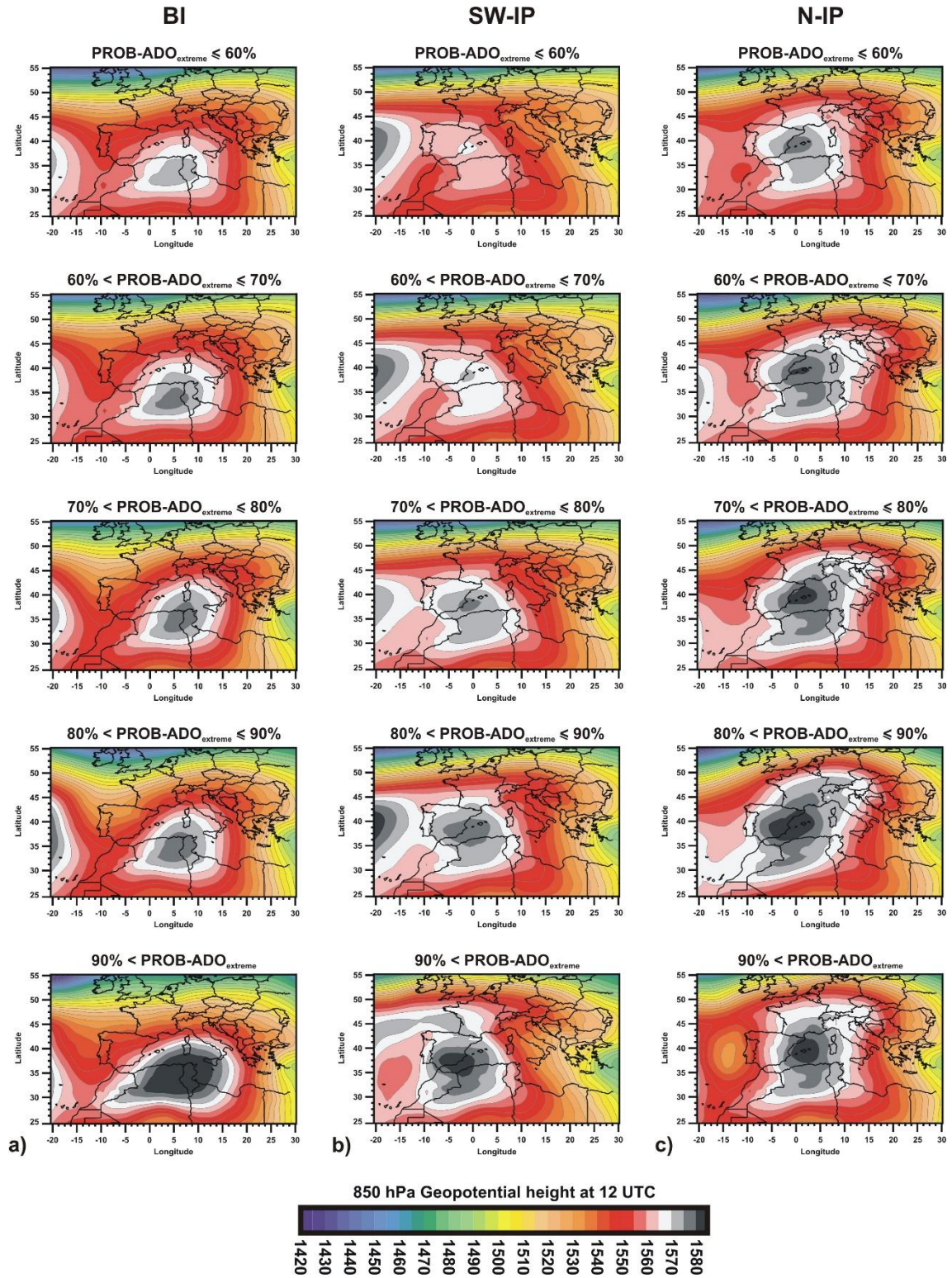


Figure 8. Composites of 850 hPa geopotential height at 12 UTC (in m) for increasing PROB-ADO extremes days under ADO-CT6 in the BI (a), SW-IP (b) and N-IP (c) sub-domains over 1940–2024.

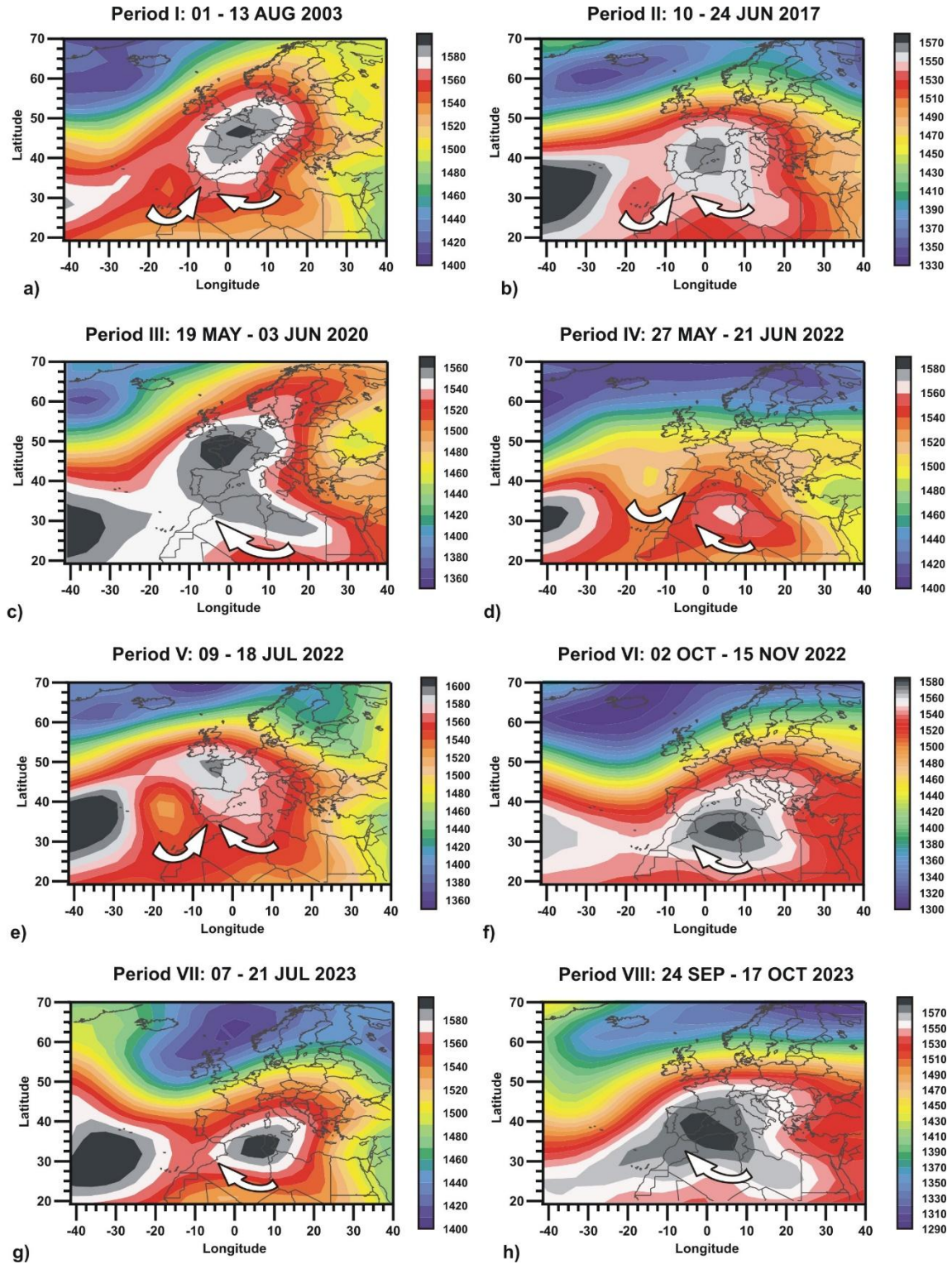


Figure 9. Composites of 850 hPa geopotential height at 12 UTC (in m) for selected persistent PROB-ADO extremes periods over NW-IP (Period I), NE-IP (Period II), CEN-IP (Period III), E-IP (Period IV), N-IP (Period V), SE-IP (Period VI), SW-IP (Period VII) and BI (Period VIII).

Table 2. Trend analysis for duration in days of consecutive PROB-ADO extremes occurrence (persistence) under all ADO-CTs in the eight sub-domains of the Iberian Peninsula (IP) and the Balearic Islands (BI) for the period 1940-2024. Values of statistically significant at the 95% confidence level slope estimators for PROB-ADO extreme persistence in days/year. NT, no statistically significant trend.

Trend estimator (days/year)	SE-IP	E-IP	SW-IP	CEN-IP	BI	NE-IP	N-IP	NW-IP
ADO-CT1	0.007	0.006	0.005	0.003	0.009	0.013	NT	NT
ADO-CT2	NT	0.006	-0.005	-0.005	0.006	-0.006	-0.010	-0.022
ADO-CT3	0.001	0.005	NT	-0.002	0.007	-0.003	-0.006	NT
ADO-CT4	0.002	0.004	0.001	0.002	-0.002	0.004	0.007	NT
ADO-CT5	NT	0.006	-0.005	-0.005	0.006	-0.006	-0.009	-0.021
ADO-CT6	0.003	0.005	0.002	NT	0.003	0.003	0.0004	0.008

Figure 9 shows several long-lasting PROB-ADO extremes persistent periods. Each period was selected based on the number of consecutive days on which PROB-ADO extremes were identified over each of the study areas. They ranged from 10 consecutive days in N-IP (Period V) to 37 days in SE-IP (Period VI), although they generally affected other regions as well. For example, during Period I (Figure 9a) selected for the NW-IP region (01–13 August 2003), which occurred during the development of the intense heatwave that occurred in parts of Europe in 2003 (García Herrera et al., 2010; Miralles et al., 2014), PROB-ADO extremes persistent periods were also detected in all the other IP sub-domains.

In all cases, composite geopotential height maps at 850 hPa showed the presence of subtropical high-pressure systems extending beyond their zonal mean latitude (subtropical ridges, Periods IV, VI, VII and VIII in Figure 9) along the 10°W–20°E transect, which in some cases have evolved into blocking patterns at higher latitudes (Periods I, II, III and V in Figure 9) with their characteristic omega shape appearance (Sousa et al., 2021). Isolated low-pressure systems (cut-off lows) have also been detected in many cases over the Atlantic Ocean to the south-west of the IP (Periods I, III, IV and V in Figure 9). Such atmospheric systems have been clearly identified both in composite maps of raw 850 hPa geopotential height data fields (Figure 9) and in maps of anomalies relative to a climatological period (supplementary Figure S10).

These type of atmospheric configurations are ideal for driving the movement of air masses of African origin over the western part of the Mediterranean basin. In fact, Cuevas-Agulló et al. (2024) and Rodríguez and López-Darias (2024) also attributed the winter extreme ADOs detected during the period 2020-2022 to cut-off lows and subtropical ridges or anticyclonic blocking over western Europe.

Other authors have identified a marked upward trend in the occurrence of anticyclonic patterns that lead to atmospheric blocking over west-central Europe (Davis et al., 1997; Horton et al., 2015). In fact, a progressive intensification and expansion of the Azores high in summer (Li et al., 2011) and winter (Cresswell-Clay et al., 2022) have been detected over the last decades, consistent with anthropogenically driven warming. It thus seems reasonable to consider that anthropogenic climate change has led to changes in the frequency and development of certain CTs that favored the occurrence of African dust transport over the western Mediterranean basin.

Conclusions.

This study has shown that the number of days with a high probability of African dust outbreaks (ADOs) occurring, defined as PROB-ADO extremes, has increased across all the Iberian Peninsula and Balearic Islands areas analysed during the period 1940–2024.

Daily PROB-ADO values were calculated using numerical models created for each study area based on a validated and recognised methodology. Three thermodynamic atmospheric parameters were used as predictor variables. PROB-ADO values have been shown to be closely linked to desert dust concentrations, both at the surface and in the atmospheric column across the study areas. Specifically, higher probabilities correspond to greater daily dust contributions to surface regional-background PM_{10} levels and to increased Aerosol Optical Thickness associated with desert dust.

Estimates of increasing trends in PROB-ADO extremes occurrence were higher in the southern and eastern parts of the Iberian Peninsula and lower in the northern third of the peninsula. As a result, between 1940 and 2024 there has been a cumulative increase of 2.7–55.7 days per year with extreme PROB-ADO values, depending on the study area.

Upward trends were also obtained for PROB-ADO extremes persistence in all regions. Such trends were more pronounced in the period 2000–2024.

Based on the results of a robust and consistent process for classifying daily synoptic circulation types, some of them associated with African dust transport (ADO-CTs), it has been possible to investigate the causes of trends attributable to dynamic and thermodynamic factors. A quantitative partitioning of the dynamic and thermodynamic contributions to the overall trend in PROB-ADO extremes, as well as to the trends associated with each CT, was performed for each region.

This study has shown that, with the exception of the north-western sector of the Iberian Peninsula (47% dynamic factors and 41% thermodynamic factors), the thermodynamic contributions to the PROB-ADO extreme trend were much greater (between 84% and 94%) than the dynamic contributions (between 9% and 18%). A spatial gradient was detected, such that dynamic contributions increased gradually with distance from the source region of desert dust.

Hence, the air masses arriving over the Iberian Peninsula - Balearic Islands domain have increasingly exhibited thermodynamic characteristics more similar to those of African origin, which in turn has been linked to a higher dust load attributable to global warming.

The six circulation patterns associated with dust transport analysed in this study made varying contributions to the increasing trends in PROB-ADO extremes, depending on the geographical region. The largest contributions came from two circulation types (ADO-CT1 and ADO-CT6), which together accounted for between 43% and 98% of the trends. Both types of synoptic weather patterns were more frequent during the summer months. They were characterised by the presence of upper-level high-pressure systems over parts of north Africa (north-eastern Algeria, Tunisia and the eastern half of Libya) and the western Mediterranean basin. A key finding is that dynamic contributions to the total trend associated with days classified as ADO-CT1 were relatively high (9–40%), whereas contributions for days under ADO-CT6 were lower (2–10%). The estimated dynamic contributions for the remaining ADO-CTs varied between 0.1% and 4%, depending on the region under study.

An analysis of the causes of these dynamic influences has revealed that, on PROB-ADO extreme days under ADO-CT1 and ADO-CT6, there was an intensification of the high-pressure centres as well as a shift to higher altitudes. Both the intensity of the high-pressure centres and their displacement, gradually increased as the range of extreme PROB-ADO values rose. The same effect occurred in all study areas, although there were variations in the position and trajectory of the high-pressure centre. Statistically significant upward trends in PROB-ADO extremes persistence were also obtained under the occurrence of ADO-CT1 and ADO-CT6 in most regions. These results suggest that an increase in the development of subtropical ridges and blocking high-pressure systems over the Mediterranean and even western Europe, sometimes accompanied by low-pressure systems over the Atlantic to the south-west of the Iberian Peninsula, are the main dynamic causes that produced the increased frequency and persistence of PROB-ADO extremes events over the regions of study.

Our results indicate that although a substantial portion of the observed increase in the daily probability of ADO occurrence has resulted from thermodynamic changes of the air masses arriving over the western Mediterranean, the risk of extreme probabilities of ADOs over all regions of the Iberian Peninsula - Balearic Islands domain has also been altered by changes in the frequency, intensity and persistence of specific circulation patterns. Although some studies have linked these changes to anthropogenic climate change, further research is still needed to confirm this point.

Methods.

Acquisition and numerical processing of meteorological parameters.

A database of values of meteorological parameters at different atmospheric levels (geopotential height at 1000, 850, and 500 hPa and temperature at 925, 850, and 700 hPa) were obtained from the "ERA5 hourly data on pressure levels from 1940 to present" reanalysis dataset (Hersbach et al., 2023) for the period 1940–2024. These data fields were downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (2023). Data were distributed in each field in a 0.25° latitude x 0.25° longitude grid.

The same type of data was obtained from the "NCEP/NCAR Reanalysis 1" (1948 to present, grid resolution 2.5° × 2.5°, Kalnay et al., 1996) and the "NOAA-CIRES-DOE 20th Century Reanalysis V3" (1806-2015, grid resolution 1° × 1°, Compo et al., 2011; Slivinski et al., 2019) reanalysis datasets.

The hourly fields of geopotential height at 850 hPa at 12 UTC in the framework 20°N - 70°N, 40°W - 40°E (Figure 1a) from the three reanalysis data sets were used to generate daily synoptic weather maps. Then, a circulation classification methodology (non-hierarchical k-means cluster analysis) was applied to group all days into one of the 11 characteristic CTs identified by Salvador et al. (2022). This analysis was carried out for each dataset covering the common period 1948–2015, in order to maintain their physical consistency and facilitate comparison between them.

The same 11 CTs obtained by Salvador et al. (2022) were used as initial clusters in each classification procedure, adapted to the different grid resolutions. Results were compared to check the robustness of the CTs classification procedure and of the analysis of their time evolution along the study period.

Daily mean values of geopotential thickness in the 1000–500 hPa layer (GT), mean potential temperature between 925 and 700 hPa (TPOT) and temperature anomalies at 850 hPa for the climatological period 1981–2010 (TANOM) were calculated for each of the eight selected sub-domains of the IP-BI region (Figure 1b) from the three reanalysis data sets (“ERA5 hourly data on pressure levels from 1940 to present”, “NCEP/NCAR Reanalysis 1” and “NOAA-CIRES-DOE 20th Century Reanalysis V3”) over the common period 1948-2015 to assess their similarity. Finally, time series of daily GT, TPOT and TANOM were used to estimate PROB-ADO with specific numerical models.

Acquisition and numerical processing of desert dust parameters.

Time series of PM₁₀ levels registered at regional background monitoring sites from the EMEP (European Monitoring and Evaluation Programme) and other regional air quality networks in each area (supplementary Figure S2) were obtained and used to quantify the net African dust contribution on the PM₁₀ daily records following a statistical procedure (Escudero et al., 2007). This method is based on the application of a moving 40th percentile with a 30-day time window to the regional background PM₁₀ daily data series, after excluding the days impacted by African dust. This way, an estimator of the daily PM₁₀ regional background without dust contributions (PM_{10_background}) is obtained. It allows to calculate the net African dust regional contribution to PM₁₀ by subtracting it from the daily PM₁₀ levels during ADO ($PM_{10_net-dust} = PM_{10} - PM_{10_background}$). A daily mean value of PM_{10_net-dust} for each identified ADO episodic day was thus determined for each sub-domain in the period 2001-2024.

This methodology was recommended by the European Commission as one of the official methods for evaluating the occurrence of ADO and quantifying desert dust contributions (Commission Staff Working Paper, 2011). A recent study that addressed the evaluation of the performance of receptor statistical methods for quantifying desert dust contributions to ambient PM₁₀ and PM_{2.5} levels, concluded that this was the best method available so far, for determining the regional PM_{10_net-dust} in European countries (Querol et al., 2026).

Additionally, we used data from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) dataset (Global Modeling and Assimilation Office (GMAO), 2015), to detect the transport of dust particles by the atmospheric circulation towards the IP-BI domain. Specifically, we employed the 550 nm dust extinction aerosol optical thickness (AOT_{dust} DUEXTTAU) to quantify dust throughout the atmospheric column. Data was available from January 1980 at a spatial resolution of 0.625° × 0.5°. We obtained daily mean data from 1980 to 2024 and averaged them over each sub-domain (Figure 1b).

Development of numerical models for estimating the daily PROB-ADO.

Daily GH, TPOT, and TANOM data obtained from the “ERA5 hourly data on pressure levels from 1940 to present” reanalysis data set were used to calculate PROB-ADO values with the numerical prediction models created for each sub-domain, following the procedure described in Salvador et al. (2024).

This procedure follows several stages.

First, it was necessary to obtain a long-term record of ADO identified over each sub-domain. This information was used to obtain a functional relationship between the values of the thermodynamic parameters and the development of ADO. To do so, a robust procedure based on the daily interpretation of several meteorological products, was used to identify all the ADOs with impact in the daily levels of PM₁₀ registered in the eight sub-domains (Querol et al., 2009; Pey et al., 2013). Firstly, back-trajectories of air masses were calculated (HYSPLIT ARL-NOAA) and interpreted to account for their transport from N Africa. Synoptic weather maps of sea level pressure and geopotential height at several pressure levels were also calculated using reanalysis data sets (NCEP/NCAR Reanalysis 1 or ERA5) to verify the existence of favorable scenarios for the transport of dust. Then, maps of dust concentration generated by numerical models (SKIRON-University of Athens; World Meteorological Organization (WMO) Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS); Copernicus Atmosphere Monitoring Service (CAMS)), and satellite images (MODIS-NASA) were evaluated. Finally, time series of PM₁₀ levels registered at regional background monitoring sites in each area (supplementary Figure S2) were obtained and used to validate the real impact of dust on surface PM₁₀ levels.

The identification of ADO over the regions of study started in 2001 because most of these databases, tools and numerical models for predicting dust concentration were not fully developed before this year. Finally, an ADO catalog containing all dust events developed in the period 2001-2024 over the eight sub-domains was obtained. It was used to calculate the number of ADOs in a sub-domain when GT, TPOT and TANOM values surpassed certain threshold levels. Initially, the percentiles of the time series of daily mean values of GT, TPOT and TANOM for each sub-domain were employed as threshold values. PROB-ADO were thus computed as the ratio of positive cases (ADO episodic days with exceeded threshold values) to possible cases (all days with exceeded threshold values from 2001 to 2024). With threshold values determined for all possible PROB-ADO between 0 and 100 %, we could assign an estimated PROB-ADO to each day of the period 2001-2024, based on the corresponding daily mean values of GT, TPOT and TANOM over each region and the threshold values that were surpassed.

Then, the multiple linear regression procedure was employed to develop a statistical prediction model for each sub-domain. In this model, the independent variables were the thermodynamic parameters GT, TPOT, TANOM and the dependent variable was PROB-ADO.

$$\text{PROB} - \text{ADO} = a_1 \cdot \text{TPOT} + a_2 \cdot \text{TANOM} + a_3 \cdot \text{GT} + a_4 \quad [1]$$

To enhance the linear fit of the models, the Box-Cox transformation procedure was applied to the dependent variable and the Cochran-Orcutt procedure was also applied to avoid autocorrelation in the residuals.

Finally, valid multi-linear regression models were obtained in all cases with R² values ranging from 81.70% in the SE-IP zone to 87.34% in the NW-IP region (supplementary Figure S1). These models were used to estimate PROB-ADO for all days of the period 1940-2024 in the eight regions of the IP-BI domain.

Estimation of trends.

To calculate temporal trends in the time series of annual frequencies of the 11 CTs and of PROB-ADO extremes, of values of PROB-ADO and of the persistence of PROB-ADO extremes (duration

in days of consecutive PROB-ADO extremes occurrence) over 1940-2024, the Theil-Sen methodology (Hirsch et al., 1982) was used. With this method, it is possible to determine trends in time series of numerical values and express the magnitude of the trend as a positive or negative slope. Said slope indicates the increase or decrease in the analysed magnitude in units of magnitude per unit of time (days/year for annual frequencies of CTs and PROB-ADO extremes occurrence and for PROB-ADO extreme persistence, and %/year for PROB-ADO). The main advantages of using this non-parametric approach are that it tends to produce accurate confidence intervals even with non-normal data and heteroscedasticity, and that it is also resistant to the presence of outliers in the time series data. The “openair” data analysis R package was used to apply the Theil-Sen method (Carslaw and Ropkins, 2012). Plots of smoothed trends for PROB-ADO were also determined with “openair” using the R function “smoothTrend”. This function fits a smooth line to the data using Generalized Additive Modelling. The amount of smoothness in the trend is optimised in the sense that it is neither too smooth nor too variable.

Estimation of causes of the trends of PROB-ADO extremes.

To determine the dynamic, thermodynamic and interactive contributions of each individual CT to the general trend in the occurrence of PROB-ADO extremes, the quantitative partitioning methodology proposed by Horton et al. (2015) was applied. According to this methodology, the frequency of days per year in a time series in which PROB-ADO extremes occurred, E , can be expressed as:

$$E = \sum_{i=1}^k E_i f_i \quad [2]$$

where f_i is the frequency of occurrence of CT_i , E_i is the frequency of PROB-ADO extreme days when circulation pattern i occurs, and k is the total number of circulation patterns (11 in this case). If we break down E and f into the components of temporal mean and deviation from the temporal mean:

$$E = \sum_{i=1}^k (\bar{E}_i + E'_i)(\bar{f}_i + f'_i) \quad [3]$$

By differentiating the equation with respect to time to estimate trends:

$$\frac{dE}{dt} = \sum_{i=1}^k (\bar{f}_i \frac{dE'_i}{dt} + \bar{E}_i \frac{df'_i}{dt} + \frac{d(E'_i f'_i)}{dt}) \quad [4]$$

The first term of the equation [4] on the left, represents the temporal trend of PROB-ADO extremes in the study area, in days per year, for all days of the period. On the right, the first and second terms represent, respectively, the thermodynamic and dynamic contributions to the overall trend in PROB-ADO extremes produced by the days on which CT_i occurred.

The thermodynamic contribution assumes that each CT_i is stationary over time and that the trends in PROB-ADO extremes for the days on which CT_i occurred are the result of influences unrelated to atmospheric circulation, such as changes in incoming long-wave radiation due to increased concentrations of greenhouse gases, or changes in surface moisture and/or radiation fluxes caused by changes in land cover. The dynamic contribution represents the portion of the trend in PROB-ADO extremes that is attributable solely to changes in CTs, assuming that the proportion of PROB-ADO extreme associated with each CT has remained unchanged.

The third term of the equation [4] on the right represents the interactive contributions resulting from changes in the dynamic component acting on changes in the thermodynamic component, such as positive or negative feedbacks from surface-atmosphere interactions.

This methodology will make it possible to partition the contributions of dynamic and thermodynamic changes to (1) the overall trend in PROB-ADO extreme occurrence and (2) the trends associated with specific circulation patterns.

Statistical methods

The statistical significance of the trend estimates for a given confidence level (at least 95%) was performed by mean of bootstrapping techniques with the “openair” data analysis tools (Carslaw and Ropkins, 2012). The time series of daily AOT_{dust} values over each sub-domain didn’t fit to normal distributions. For this reason, the Mann-Whitney non parametric test was used to search for statistically significant differences between the medians corresponding to PROB-ADO extreme days and the whole period, for a 95% confidence level. The R Stats package was used to perform these tests.

Code availability

The Python script created for performing the circulation classification procedure is available from the corresponding author on reasonable request.

Funding declaration

This study was funded by research projects POSAHPI-2 (Government of Spain, State Research Agency, grant PID2022-143146OB-I00), PRODUST (Government of Spain, State Research Agency, grant PID2025-169249OB-I00) and “Study of Saharan dust during the Holocene using advanced observation techniques in sedimentary records, and prediction of future scenarios using climatology in digital environments” (Ministry of Science, Innovation and Universities – Special grants to attract talent with digital skills: “CSIC MOMENTUM PROGRAMME: DEVELOP YOUR DIGITAL TALENT”, grant MMT24-IPE-02).

Referencias:

- Alonso-Perez, S. et al. (2011). Trend changes of African airmass intrusions in the marine boundary layer over the subtropical Eastern North Atlantic region in Winter. *Tellus* 63B, 255–265.
- Blackport, R., and Screen, J. A. (2020). Insignificant effect of arctic amplification on the amplitude of midlatitude atmospheric waves. *Sci. Adv.*, 6(8), eaay2880.
- Carslaw, D. C. and Ropkins, K. (2012). Openair - an R package for air quality data analysis. *Environ. Modell. Softw.* 27-28, 52–61.
- Cattiaux, J. et al. (2016). Sinuosity of midlatitude atmospheric flow in a warming world. *Geophys. Res. Lett.*, 43(15), 8259–8268.
- Commission Staff Working Paper (2011). Establishing guidelines for demonstration and subtraction of exceedances attributable to natural sources under the Directive 2008/ 50/EC on ambient air quality and cleaner air for Europe, Brussels, 15.02.2011. SEC (2011) 208 final.
- Compo, G.P., Whitaker, J.S., Sardeshmukh, P.D., et al., 2011. The Twentieth Century Reanalysis Project. *Q.J.R. Meteorol. Soc.*, 137: 1-28. <https://doi.org/10.1002/qj.776>.
- Copernicus Climate Change Service (C3S) (2023): ERA5 hourly data on pressure levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). 10.24381/cds.bd0915c6 (Accessed on 23-Jun-2025).
- Cresswell-Clay, N., Ummenhofer, C. C., Thatcher, D. L., Wanamaker, A. D., Denniston, R. F., Asmerom, Y., Polyak, V. J. (2022). Twentieth-century Azores High expansion unprecedented in the past 1,200 years. *Nature Geoscience*, 15(7), 548-553.
- Cuevas-Agulló, E. et al. (2024). Sharp increase in Saharan dust intrusions over the western Euro-Mediterranean in February–March 2020–2022 and associated atmospheric circulation. *Atmos. Chem. Phys.*, 24, 4083–4104.
- Davis, R. E., Hayden, B. P., Gay, D. A., Phillips, W. L., & Jones, G. V. (1997). The north Atlantic subtropical anticyclone. *Journal of Climate*, 10(4), 728-744.
- Díaz, J. et al. (2017). Saharan dust intrusions in Spain: health impacts and associated synoptic conditions. *Environ. Res.* 156, 455–467.
- EC, 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe, OJ L 152, 11.6.2008, pp. 1–44. <https://eur-lex.europa.eu/eli/dir/2008/50/oj>
- EC, 2024. Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast), <http://data.europa.eu/eli/dir/2024/2881/oj>
- Escudero, M. et al. (2005). Wet and dry African dust episodes over Eastern Spain. *J. Geophys. Res.* 110, D18S08 10.1029.
- Faranda, D. et al. (2023). Atmospheric circulation compounds anthropogenic warming and impacts of climate extremes in Europe. *Proc. Natl. Acad. Sci. U.S.A.*, 120(13), e2214525120.
- García-Herrera, R., Díaz, J., Trigo, R. M., Luterbacher, J., & Fischer, E. M. (2010). A review of the European summer heat wave of 2003. *Critical Reviews in Environmental Science and Technology*, 40(4), 267-306.
- Gillet, N.P., Graf, H.F. & Osborn, T.J. Climate Change and the North Atlantic Oscillation. Chapter in *The North Atlantic Oscillation: Climatic Significance and Environmental Impact* (Published by the American Geophysical Union as part of the Geophysical Monograph Series, 134., Washington, DC, Editor(s): Hurrell, J. W., Kushnir, Y., Ottersen, G. & Visbeck, M.), <https://doi.org/10.1029/134GM09> (2003).
- Ginoux, P. et al. (2012). Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. *Rev. Geophys* 50, RG3005.
- Global Modeling and Assimilation Office (GMAO). (2015). MERRA-2 tavg1_2d_aer_Nx: 2d, 1-Hourly, time-averaged, Single-Level, Assimilation, Aerosol Diagnostics V5.12.4 [dataset].

Accessed: 2024-04-18. Goddard Earth Sciences Data and Information Services Center (GES DISC). doi: 10.5067/KLILCLTZ8EM9D.

Goudie A. S. & Middleton N.J. (2006). Desert Dust in the Global System. (Springer, Heidelberg, <https://doi.org/10.1007/3-540-32355-4>).

Heffernan, O. (2016). The mystery of the expanding tropics. *Nature* 530, 20–22.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J.-N., 2023. ERA5 hourly data on pressure levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.bd0915c6 (Accessed on 01-Feb-2025).

Hirsch, R., Slack, J. R. & Smith, R. A. Techniques of trend analysis for monthly water quality data. *Water Resour. Res* 18, 107–121 (1982).

Horton, D. E. et al. (2015). Contribution of changes in atmospheric circulation patterns to extreme temperature trends. *Nature*, 522(7557), 465–469.

Jézéquel, A. et al. (2018). Trends of atmospheric circulation during singular hot days in Europe. *Environ. Res. Lett.*, 13(5), 054007.

Kalnay et al., 1996. The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteor. Soc.*, 77, 437–470.

Li, W., Li, L., Fu, R., Deng, Y., & Wang, H. (2011). Changes to the North Atlantic subtropical high and its role in the intensification of summer rainfall variability in the southeastern United States. *Journal of Climate*, 24(5), 1499–1506.

Mann, M. E. et al. (2018). Projected changes in persistent extreme summer weather events: The role of quasi-resonant amplification. *Sci. Adv.*, 4, eaat3272.

Marshall, J. North Atlantic climate variability: phenomena, impacts and mechanisms. *Int. J. Climatol.* 21, 1863–1898 (2001).

Martin, J. E. (2021). Recent trends in the waviness of the northern hemisphere wintertime polar and subtropical jets. *J. Geophys. Res. Atmos.*, 126(9), e2020JD033668.

Martin, J. E., and Norton, T. (2023). Waviness of the southern hemisphere wintertime polar and subtropical jets. *Weather Clim. Dyn.*, 4(4), 875–886.

Masson-Delmotte, V. et al. (2021). Climate change 2021: The physical science basis. contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change (Vol. 2). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. doi: 10.1017/9781009157896.

Miralles, D. G., Teuling, A. J., van Heerwaarden, C. C., Vila-Guerau de Arellano, J. (2014). Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. *Nat. Geosci.* 7, 345–349.

Pérez, L. et al. (2008). Coarse particles from Saharan dust and daily mortality. *Epidemiology* 19, 800–807.

Pérez, L. et al. (2012). Effects of local and Saharan particles on cardiovascular disease mortality. *Epidemiology* 23, 768–769.

Pérez-Martínez, C. et al. (2020). Long-term ecological changes in Mediterranean mountain lakes linked to recent climate change and Saharan dust deposition revealed by diatom analyses. *Sci. Total Environ.* 727, 138519.

Pey, J. et al. (2013). African dust outbreaks over the Mediterranean Basin during 2001–2011: PM10 concentrations, phenomenology and trends, and its relation with synoptic and mesoscale meteorology. *Atmos. Chem. Phys.* 13, 1395–1410.

Pons, F. et al. (2025). Assessing climate change impacts on the March 2024 compound floods and Saharan dust outbreak in Europe. *J. Geophys. Res. Atmos.*, 130, e2024JD042218.

Prospero, J. M. (2006). Saharan dust impacts and climate change. *Oceanography* 19, 60–61.

Prospero, J.M. and Lamb, P.J. (2003). African droughts and dust transport to the Caribbean: climate change implications. *Science* 302 (5647), 1024–1027.

- Querol, X., Pey, J., Pandolfi, M., Alastuey, A., Cusack, M., Pérez, N., ... & Kleanthous, S. (2009). African dust contributions to mean ambient PM₁₀ mass-levels across the Mediterranean Basin. *Atmospheric Environment*, 43(28), 4266–4277.
- Querol, X., Alastuey, A., Pey, J., Salvador, P., González-Romero, A., & Pérez, N. (2026). Evaluation of the performance of receptor statistical methods for quantifying desert dust contributions to ambient particulate for health studies and policy. *Atmospheric Environment*, 121831.
- Riboldi, J. et al. (2020). On the linkage between rossby wave phase speed, atmospheric blocking, and arctic amplification. *Geophys. Res. Lett.*, 47(19), e2020GL087796.
- Ridame, C. et al. (2014). Contrasted Saharan dust events in LNL environments: impact on nutrient dynamics and primary production. *Biogeosciences* 11, 4783–4800.
- Rogers, C. D. et al. (2022). Sixfold increase in historical northern hemisphere concurrent large heatwaves driven by warming and changing atmospheric circulations. *J. Clim.*, 35(3), 1063–1078.
- Rodríguez, S. and López-Darias, J. (2024). Extreme Saharan dust events expand northward over the Atlantic and Europe, prompting record-breaking PM₁₀ and PM_{2.5} episodes, *Atmos. Chem. Phys.*, 24, 12031–12053.
- Salvador, P. et al. (2013). African dust contribution to ambient aerosol levels across central Spain: Characterization of long-range transport episodes of desert dust. *Atmos. Res.* 127, 117–129.
- Salvador P. et al. (2014). African dust outbreaks over the western Mediterranean basin: 11 year characterization of atmospheric circulation patterns and dust source areas. *Atmos. Chem. Phys.* 14, 6759–6775.
- Salvador P. et al. (2022). Increasing atmospheric dust transport towards the western mediterranean over 1948–2020. *npj Clim. Atmos. Sci.*, 5(1), 34.
- Salvador P. et al. (2024). Estimating the probability of occurrence of African dust outbreaks over regions of the western Mediterranean basin from thermodynamic atmospheric parameters. *Sci. Total Environ.*, 922:171307.
- Sánchez-Benítez, A., García-Herrera, R., Barriopedro, D., Sousa, P.M., Trigo, R.M., 2018. June 2017: the earliest European summer mega-heatwave of reanalysis period. *Geophys. Res. Lett.* 45, 1955–1962. <https://doi.org/10.1002/2018GL077253>.
- Shepherd, T. G. (2014). Atmospheric circulation as a source of uncertainty in climate change projections. *Nat. Geosci.* 7, 703–708.
- Slivinski L.C., Compo G.P., Whitaker J.S., et al., 2019. Towards a more reliable historical reanalysis: Improvements for version 3 of the Twentieth Century Reanalysis system. *Q J R Meteorol Soc.*; 145: 2876–2908. <https://doi.org/10.1002/qj.3598>.
- Sousa, P.M., Barriopedro, D., Ramos, A.M., García-Herrera, R., Espírito-Santo, F., Trigo, R.M., 2019. Saharan air intrusions as a relevant mechanism for Iberian heatwaves: the record breaking events of August 2018 and June 2019. *Weather. Clim. Extremes* 26, 100224. <https://doi.org/10.1016/j.wace.2019.100224>.
- Stafoggia, M. et al. (2016). Desert dust outbreaks in southern Europe: contribution to daily PM₁₀ concentrations and short-term associations with mortality and hospital admissions. *Environ. Health Perspect.* 124, 413–419.
- Thomas, N. and Nigam, S. (2018). Twentieth-century climate change over Africa: seasonal hydroclimate trends and Sahara Desert expansion. *J. Clim.* 31, 3349–3370.
- Varga, G. (2020). Changing nature of Saharan dust deposition in the Carpathian Basin (Central Europe): 40 years of identified North African dust events (1979–2018). *Environ. Int.* 139, 105712.
- WHO, 2021. WHO global air quality guidelines. Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. ISBN 978-92-4-003422-8 (electronic version). 273 pp.
- Zucca, C. et al. (2021). Shrinking water bodies as hotspots of sand and dust storms: The role of land degradation and sustainable soil and water management. *Catena* 207, 105669.

Acknowledgements

The research team acknowledges the continued financial support by the Ministry for the Ecological Transition and the Demographic Challenge of Spain for the evaluation of the desert dust contributions to PM₁₀ and PM_{2.5} across the whole Spain.

The authors extend their gratitude to the NOAA PSL, Boulder, Colorado, USA for providing access to the NCEP-NCAR Reanalysis 1 data and the NOAA/CIRES/DOE 20th Century Reanalysis (V3) data. Support for the Twentieth Century Reanalysis Project version 3 dataset is provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER), by the National Oceanic and Atmospheric Administration Climate Program Office, and by the NOAA Earth System Research Laboratory Physical Sciences Laboratory. Hersbach et al. (2023) was downloaded from the Copernicus Climate Change Service (C3S) (2023). The results contain modified Copernicus Climate Change Service information 2023. Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

The authors also acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT trajectory model, the Atmospheric Modelling & Weather Forecasting Group- University of Athens, World Meteorological Organization (WMO) Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS), the Copernicus Atmosphere Monitoring Service (CAMS) and the MODIS-NASA for the provision of the SKIRON dust concentration maps, the multi-model ensembles of dust concentration at surface and the satellite imagery, respectively.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SUPPLEMENTARYMATERIAL.docx](#)