



Disentangling dust transport pathways to western Crete using aerosol measurements and HYSPLIT trajectories

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Abstract. Mineral dust transported to the eastern Mediterranean affects atmospheric conditions, radiation balance, soil
10 development processes, and ecosystem functioning in deposition areas. While the dominant source regions of deposited dust
can be roughly identified with the help of sediment fingerprinting approaches, different methodological challenges hamper the
exact identification of aeolian sediment sources and their potential temporal and spatial shifts. This study evaluates whether
the combination of ground-based aerosol concentration measurements and backward-trajectory modelling can provide a
temporally more resolved perspective on dust-source variability in western Crete. With this aim, aerosol concentrations from
15 a monitoring network in and around the Lefka Ori mountains were used to identify days with elevated surface-near dust loads
between October 2023 and September 2025. For these days, air-mass pathways were reconstructed using the atmospheric
transport and dispersion modelling system HYSPLIT, and grouped into recurring transport patterns. The resulting clusters
show that elevated aerosol concentrations were primarily associated with transport from southern directions representing North
Africa, especially Libya and Egypt, but also with frequent northerly pathways connecting Crete to the Balkan, the Black Sea
20 region and eastern Europe. Clusters summarising southerly transport patterns showed the strongest seasonal relevance during
the main dust season in spring and were associated with higher aerosol concentrations, whereas clusters associated with
northerly transport patterns occurred frequently but were generally associated with lower aerosol concentrations. The applied
method enabled a temporally high resolved assessment of dust source regions, thereby revealing subordinate but nevertheless
relevant source areas. Future work should combine longer observation periods with chemical, mineralogical, and isotopic
25 analyses to quantify the relative contribution of these source regions to the deposited dust.

1 Introduction

Mineral dust transportation represents one of the most important forms of long-range sediment transfer on Earth, involving the
atmospheric transport of large quantities of material over continental to intercontinental distances (Goudie and Middleton
2006; Prospero et al. 2002; Shao et al. 2011; Uno et al. 2009). Among global dust-producing regions, North Africa is the
30 dominant source, releasing an estimated 400 to 2,200 Tg of mineral particles into the atmosphere each year (Huneeus et al.



2011). These aerosol particles typically have diameters between 0.1 and 100 μm (Mahowald et al. 2014). Once emitted, mineral dust has wide-ranging environmental effects. Elevated dust concentrations are associated with adverse impacts on human health (Monteiro et al. 2022; Schwartz et al. 1996), while atmospheric dust also plays an important role in modifying the Earth's radiation balance (Gkikas et al. 2019; Miller and Tegen 1999; Shao et al. 2011). Beyond its atmospheric relevance, deposited dust may contribute to soil development and can modulate ecosystem processes and biological productivity in receiving regions (Herrmann et al. 1996; Simonson 1995). The magnitude and spatial as well as temporal variability of dust transport and deposition patterns are controlled by the interplay of synoptic transport mechanisms, and site specific factors such as topography, which can modify local wind fields (Heisel et al. 2021; Lapere et al. 2024; Lawrence and Neff 2009). A considerable fraction of North African dust, estimated at up to 15%, is transported into the Mediterranean region (Shao et al. 2011; Stuut et al. 2009). One main transport pathway to the Eastern Mediterranean region is dominated by Sharav cyclones, mainly in the so-called dust season between March and May (Israelevich et al. 2002; Flaounas et al. 2015).

The mineralogical composition and isotope ratios of deposited dust allow for the dominant source regions of the deposited material to be identified (Guinoiseau et al. 2022; Crocker et al. 2025; Blanchet 2019; Pichat et al. 2014). However, outside major dust events, deposition rates are rather low, hampering temporally highly resolved passive sampling of clearly attributable dust deposits. As a result, the analysis of these deposits reflects a mixed composition of dust particles originating from multiple source regions (Bitzan et al. 2026a; Guieu et al. 2002; Formenti et al. 2003; Formenti et al. 2008). While fingerprinting approaches allow the dominant source regions of deposited dust to be identified by comparing mineralogical, isotopic, or geochemical parameters with source-specific reference compositions, minor or overlapping source contributions may remain unresolved, particularly where source signatures are similar or where mixed samples integrate material from several transport events (Grousset and Biscaye 2005; Formenti et al. 2011; Újvári et al. 2012; Scheuvens et al. 2013).

Transport pathways from the dominant source regions to the eastern Mediterranean are largely controlled by seasonally varying wind systems and their associated pressure patterns. However, these seasonal circulation regimes do not translate into a temporally uniform contribution of individual source areas. Instead, dust transport is highly episodic and depends on the timing, position, intensity and vertical structure of individual synoptic systems, as well as on the activation of specific source areas and the prevailing transport height (Israelevich et al. 2012; Varga et al. 2014; Schepanski et al. 2016; Gkikas et al. 2016; Marinou et al. 2017). Consequently, there is still limited knowledge of how the relative contribution of individual dust source and influence regions varies at sub-seasonal to event scale. The temporal resolution of provenance analyses can be improved by incorporating satellite observations, which have been widely used to identify dust plumes, derive dust-event climatologies, and analyse the spatial and seasonal variability of aerosol loads over the Mediterranean region (Moulin et al. 1998; Israelevich et al. 2002; Barnaba and Gobbi 2004; Kalivitis et al. 2007; Gkikas et al. 2013). Such approaches allow dust transport to be assessed at much higher temporal coverage than is usually possible from passive deposition sampling or geochemical provenance analyses alone. However, satellite products primarily describe dust in suspension, for example through aerosol optical depth or absorbing aerosol indices, and therefore do not quantify the near surface amount of mineral dust (Lawrence



and Neff 2009; Huneus et al. 2011; Bitzan et al. 2025). Therefore, satellite-based and trajectory-based approaches need to be
65 constrained by ground-based aerosol observation.

The island of Crete in the eastern Mediterranean is well suited for investigating dust deposition regarding its provenance because of its location close to the North African dust source regions, its isolated setting, and a diverse topography reaching elevations well above the zone of marine impact. These characteristics make Crete an ideal natural setting for assessing seasonal variations in the relative importance of different dust sources.

70 In this study, we combine ground-truth ground level aerosol concentration measurements from eight sites around the Lefka Ori mountain range in western Crete with HYSPLIT backward trajectories to improve the temporal resolution of provenance analysis; ground-truth aerosol measurements are used to constrain and validate the relevant time periods for dust transport, while back-trajectories are used to identify the associated atmospheric dust transport pathways.

The overall aim of this study is to evaluate whether the integration of aerosol concentration measurements from deposition
75 areas with backward-trajectory modelling provides a temporally more resolved perspective on dust-source regions. The combination of methods is used to isolate transport pathways associated with surface-near increases in aerosol concentrations and to compare these trajectory-derived source regions with previously published provenance patterns inferred from fingerprinting approaches of deposited dust. This comparison allows for the assessment of the degree of agreement between trajectory-based and sampling-based provenance approaches, while also potentially identifying additional source regions that
80 are not typically regarded as dominant contributors to dust in the Eastern Mediterranean. Furthermore, this study investigates the temporal variability of these source regions and intends to relate their occurrence to potentially season specific atmospheric circulation patterns.



2. Material and methods

2.1 Environmental setting

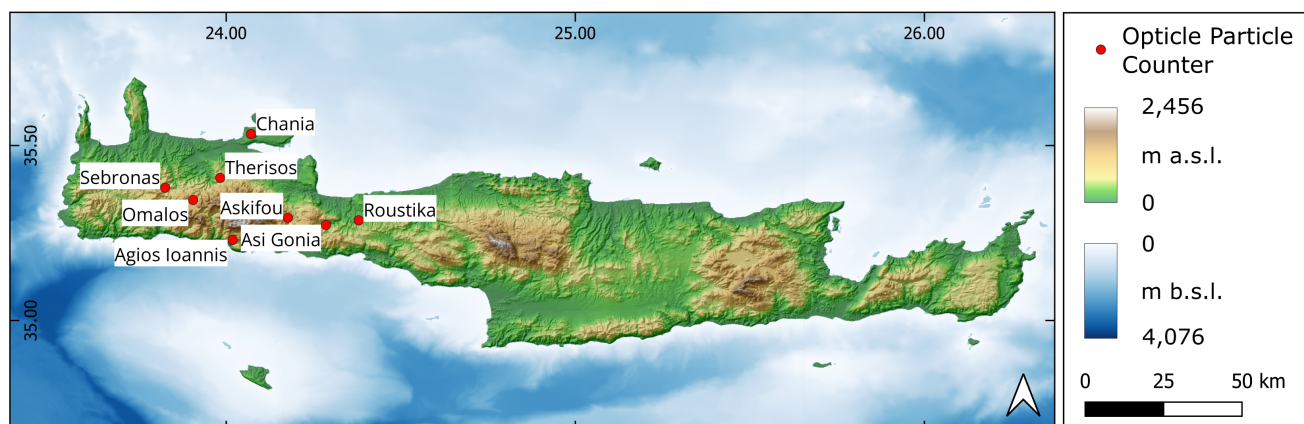


Figure 1: Topographic map of Crete with measurement stations indicated by red points; data sources (EMODnet Bathymetry Consortium 2024; Copernicus Land Monitoring Service / European Environment Agency 2016).

85 The largest Greek island Crete lies in the Eastern Mediterranean approximately 95 km southeast of the Peloponnese and about 285 km north of the Libyan coast (Fig. 1). It has a latitudinal extent of ca. 0.8° and a longitudinal extent of about 2.8° . The island is characterized by three mountain ranges that run along an east-west axis and reach a maximum elevation of 2,456 m a.s.l. The western part of Crete is characterized by particularly rugged relief, including deeply incised and narrow gorges on the southern flank, whereas the northern slopes show comparatively smoother topography. Continued tectonic uplift
 90 has promoted strong erosional incision and has been a key factor in the development of the island's major gorges, especially along the southern coast (Macklin et al. 2022).

Beside the geographical location and geomorphology, mineral dust deposition may also influence ecological conditions and soil-forming processes (Goudie & Middleton 2001, Herrmann et al. 1996). In the eastern Mediterranean, mineral dust transport is most pronounced during spring, with the main dust season extending from March to May, when long-range transport from
 95 North Africa reaches its highest intensity (Moulin et al. 1997; Nabat et al. 2015). Spring dust outbreaks in this region are primarily associated with Sharav cyclones, which are low-pressure systems forming over Libya or Algeria. These systems typically move northwestward before progressing eastward along the North African coastline, thereby facilitating dust transport into the eastern Mediterranean (Fiedler et al. 2014; Israelevich et al. 2002; Moulin et al. 1997). Between May and September, atmospheric circulation is dominated by the northerly Meltemi winds. This dry, relatively cool, and typically dust-
 100 poor airflow limits the advection of dust from southern source regions (Dafka et al. 2019; Hyder et al. 2002).

Beyond the main spring dust period, further but generally less intense contributions to the regional dust burden have been identified from Egyptian sources particularly during July and August. Additional contributions from the Libyan coastal region have been reported between September and November and are mainly relevant for the easternmost part of the Mediterranean



basin (Israelevich et al. 2003). Taken together, based on current knowledge, dust reaching Crete is predominantly transported
105 along pathways approaching from the south to southwest.

2.2 Aerosol concentration data (Measurement design OPCs)

The aerosol concentration data used in this study were obtained from a measurement network consisting of eight optical particle
counters (OPCs) installed in and around the Lefka Ori mountain range in western Crete (Bitzan et al. 2025). The stations cover
an elevation gradient from 310 m a.s.l. at Roustika to 1,040 m a.s.l. on the Omalos Plateau. The analysed time period extends
110 from October 2023 to September 2025. For logistical reasons and to ensure regular maintenance of the instruments, the
monitoring sites were selected at locations that are accessible throughout the year. All stations are situated in or close to small
villages and at least 10 km away from urban areas in order to minimize potential influences from traffic-related air pollution.
Land use in the surroundings of the stations is mainly characterized by olive groves and small-scale livestock grazing. Only
the areas surrounding the Askifou and Omalos stations are subject to more intensive agricultural activity, including field
115 cultivation and soil tillage.

The OPCs are based on the SEN54 environmental node manufactured by Sensirion AG, Stäfa, Switzerland. Aerosol
concentrations in the PM_{1.0} and PM_{2.5} size fractions are measured by laser scattering, whereas PM_{4.0} and PM₁₀
concentrations are estimated by applying typical aerosol particle size distributions derived from PM_{0.5}, PM_{1.0}, and PM_{2.5}
measurements. The temporal resolution of the aerosol concentration measurements is 10 s. Detailed information on the
120 technical specifications, precision, accuracy, and error ranges of the instruments is provided by Bitzan et al. (2025). In this
study, only OPC measurements obtained under relative humidity conditions of $\leq 95\%$ were included, in order to prevent the
use of data that may have been biased by condensation effects.

2.3 Definition of “dust days”

The use of backward trajectories to identify source regions of dust reaching Crete requires that only trajectories from days with elevated aerosol concentrations in the deposition area are considered. Our classification of dust days, and thus the selection of days included in the trajectory analysis, is based on the OPC data described in Section 2.2. To define a threshold, daily geometric mean PM10 concentrations were calculated for each station and each day during the observation period (Fig. 2). The percentile distribution of daily mean values for the entire observation period and across all stations shows a marked increase in slope at the 85th percentile (Fig. 3). As the lower percentile range is characterised by a comparatively constant slope, we interpret this increase as a shift in environmental conditions associated with dust events and, consequently, with aerosols originating from sources outside Crete. The resulting threshold for the daily mean PM10 concentration at the 85th percentile is 8.16 $\mu\text{g}/\text{m}^3$.

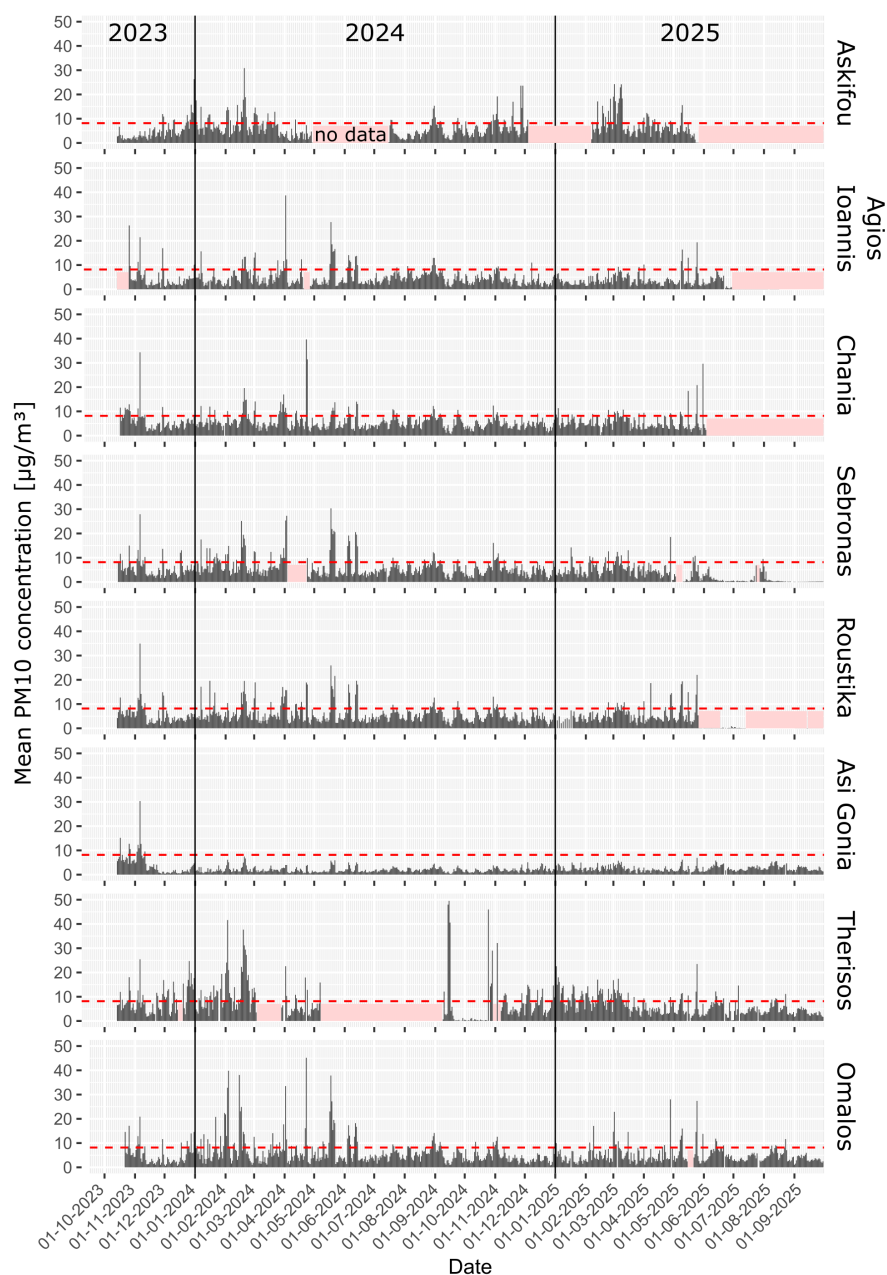


Figure 2: Daily mean PM10 aerosol concentration at the different stations. Red dashed line indicates threshold for classification of dust days within this study. Periods with “no data” are indicated with a pink rectangle for each station.



To assess whether the use of PM10 values may introduce a bias because they represent only estimates based on measurements of the smaller fractions, within the SEN environmental node (see Section 2.2.), the same procedure was applied to the PM2.5 data (data not displayed). The resulting distribution did not differ significantly from that obtained for PM10, supporting the use of daily mean

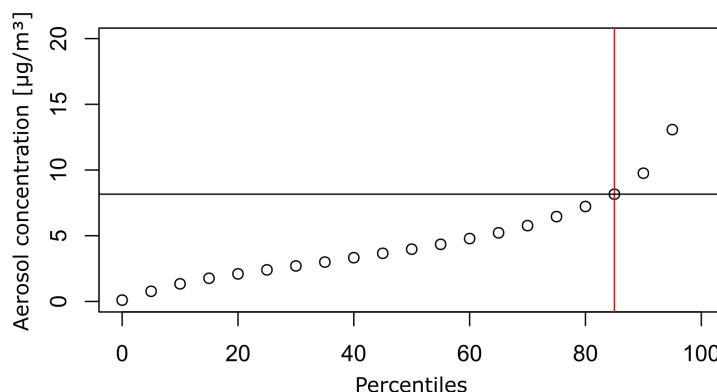


Figure 3: Percentiles of daily mean PM10 aerosol concentrations in 5%-steps; red line – 85th percentile; black line – aerosol concentration at 85th percentile = 8.16 µg/m³.

As expected, the number of stations at which the daily mean concentration of 8.16 µg/m³ was exceeded, varies throughout the observation period (Fig. 4).

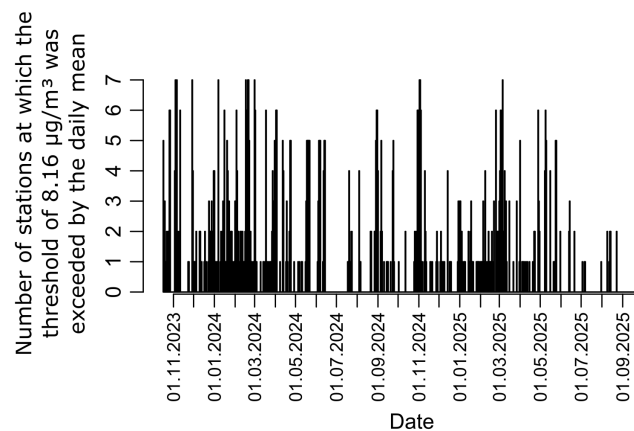


Figure 4: Number of stations exceeding threshold for each day in the observation period (715 days)

The higher the number of stations identifying a given day as a dust day, the more robust the assumption of island-wide elevated aerosol concentrations becomes. If the threshold is exceeded at only one station, local disturbances, such as local, human-induced dust emission or resuspension of dust, may have contributed to the elevated values at that particular station. Conversely, restricting the back-trajectory-analysis to days on which all eight stations recorded elevated concentrations would risk excluding actual dust days, because individual instruments were temporarily out of order or obstructed, for example by spider webs. An overview of the cumulative number of dust days as a function of the number of stations identifying them as such shows that the decrease in detected dust days stabilizes above a threshold of three stations (Fig. 5).

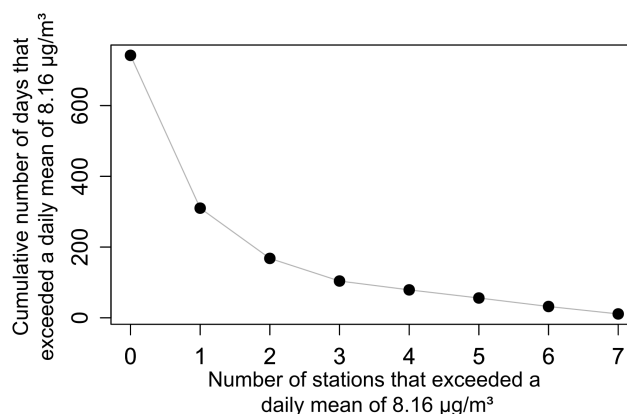


Figure 5: Number of days in the observation period and number of stations that identified them as dust days.



2.4 Trajectories

2.4.1 Trajectory modelling

Backward trajectories were calculated for all days that met the criterion of exceeding the daily mean threshold of $8.16 \mu\text{g}/\text{m}^3$ at a minimum of three monitoring stations (see Section 2.3). Trajectories were computed using the HYSPLIT Lagrangian model (Stein et al. 2015) based on the NCEP/NCAR Reanalysis dataset (Kalnay et al. 1996; NOAA ARL 2026), which has a horizontal grid spacing of 2.5° . Although the 2.5° grid does not resolve local topographic wind effects, it is suitable for the synoptic-scale classification of air-mass transport pathways towards Crete. Similar NCEP/NCAR-based HYSPLIT and composite analysis approaches have been widely applied in Mediterranean dust-transport studies (Di Iorio et al. 2009; Varga et al. 2014; Denjean et al. 2016; Dimitriou and Kassomenos 2018; Nastos 2012). The use of the NCEP/NCAR Reanalysis dataset ensured temporal consistency during the observation period, as the dataset was produced using a fixed data assimilation and model framework and was continuously updated with near-real-time observations until its discontinuation in March 2026 (NOAA ARL 2026). Thus, no change in the underlying reanalysis system affected the period analysed in this study.

For each dust day, four trajectories were calculated at 6 h intervals, corresponding to arrival times of 00:00, 06:00, 12:00, and 18:00 UTC. Each trajectory represents the pathway of the air mass during the 96 h prior to its arrival at the receptor site, with hourly output steps resulting in 96 coordinate points per trajectory. As described in Bitzan et al. (2026a), the deposited dust at the different measurement stations is very similar in its grain-size distribution as well as mineralogical and isotopic composition and accordingly in its source region. Therefore, we focus on one location in the subsequent analysis. Only trajectories for the site Agios Ioannis Sfakion are used, as this site was found to be representative of the percentile distribution of daily mean PM₁₀ aerosol concentration (Fig. S1) and of the trajectory patterns observed across all monitoring locations (Fig. S2).

The trajectories used in the main analysis were modelled for arrival at ground level based on pressure data. To assess whether trajectories that arrive at ground level are representative of transport within the planetary boundary layer, additional trajectories were calculated for pressure levels corresponding to an arrival altitude of 200 and 500 m above ground level. As no significant differences were observed between the trajectories arriving at ground level, at 200 m, and at 500 m trajectories (Fig. S3), the approach was considered representative and was retained for the subsequent analyses.

2.4.2 Cluster analyses of Trajectories

To group the individual trajectories into clusters representing a similar pathway and therefore a similar source region of the transported aerosols, a hierarchical cluster analysis was used. To identify recurring transport pathways, pairwise distances between all trajectory lines were calculated using the Fréchet distance. This metric is particularly suitable for comparing trajectory shapes because it evaluates the spatial similarity of complete curves rather than relying only on individual points or endpoints, while preserving the order of the trajectory vertices along the curve (Alt and Godau 1995; Bombelli et al. 2017). Since the trajectory vertices are ordered chronologically, this also accounts for the temporal sequence of the air-mass pathway.



The resulting distance matrices were then used as input for hierarchical clustering. For each subset, the hierarchical clustering tree was cut into ten clusters that represent groups of trajectories with similar transport pathways and were subsequently used to visualize dominant air-mass transport patterns. The same clustering procedure was also carried out with the trajectories modelled for the pressure levels representing an arrival altitude of 200 and 500 m a.s.l. but led again to very similar results, as all levels are located within the well-mixed boundary layer.

2.4.3 Pressure composites

To investigate the synoptic-scale pressure conditions associated with the identified dust transport pathways (Clusters 1-10), sea-level pressure (SLP) composites were calculated for each trajectory cluster. The analysis was based on daily SLP fields from the NCEP/NCAR Reanalysis dataset (Kalnay et al. 1996), the same that was used in the calculation of the trajectories. First, a 30-year reference climatology was derived for the period 1991-2020. For each day of the year, a climatological median SLP field was calculated from all available daily fields between 1991 and 2020. This resulted in a day-of-the-year resolved climatology that accounts for the seasonal cycle in regional pressure conditions.

The cluster-specific pressure analysis was performed for the PM₁₀-based trajectory dataset ('dust days', cf. Section 2.3) only including trajectories from days on which at least three stations recorded a daily mean aerosol concentration above 8.16 µg/m³ between October 2023 and September 2025, using the clustered trajectories arriving at Agios Ioannis Sfakion as reference. For each trajectory cluster, all unique dates associated with the selected time lag (0, 24, 48, 72 and 96 h before arrival) were extracted. Clusters represented by fewer than five dates were excluded from the composite analysis. For the remaining clusters, daily SLP fields from the analysis period were matched to the corresponding cluster dates. To remove the seasonal background signal, each daily SLP field was expressed as an anomaly relative to the 1991-2020 climatological median of the respective day of the year. Cluster-level SLP anomaly composites were then calculated as the cell-wise median of all daily anomaly fields belonging to the respective trajectory cluster.

The statistical significance of the cluster specific SLP anomaly patterns was assessed using a bootstrap approach. For each cluster, 1,000 random samples were drawn from all available dates in the analysis period, with the sample size matching the number of all dates represented in the respective cluster. For each bootstrap sample, daily SLP anomalies were calculated relative to the corresponding day-of-year climatology, and a median anomaly composite was derived. This procedure generated, for each grid cell, a bootstrap-based reference distribution of median SLP anomalies expected under random sampling of dates from the analysis period. Cluster anomalies were considered statistically significant where they fell outside the 2.5th and 97.5th percentiles of the bootstrap distribution, corresponding to a significance level of $\alpha = 0.05$.

For visualization, the median SLP anomaly fields were added to the corresponding cluster-specific median climatological SLP fields in order to display the reconstructed pressure pattern associated with each trajectory cluster.

For each trajectory, the procedure was repeated for 24, 48, 72 and 96 h before arrival to visualize the pressure distribution development leading to the corresponding trajectory.



2.4.4 Regression analyses

To assess whether the occurrence of individual trajectory clusters varied systematically between months, a regression analysis was performed on the cluster data of the station Agios Ioannis Sfakion. The trajectory cluster assignment was treated as a categorical response variable, using the ten-cluster classification derived from the cluster analysis on the HYSPLIT backward trajectories. The corresponding month was used as the explanatory variable. Months were not consolidated across the years of observation but retained as individual month labels in order to preserve the temporal structure of the observation period.

A multinomial logistic regression model was fitted with trajectory cluster membership as the response variable and month as the predictor. This approach allows the relative probability of occurrence of each trajectory cluster to be estimated for each month while accounting for the multinomial nature of the cluster assignments. The models were fitted using the *multinom* function from the R package *nnet* (Ripley 2009).

To identify significant differences in cluster occurrence between individual months, estimated marginal means were calculated from each model on the response scale using the *emmeans* package. Pairwise comparisons between months were then performed separately for each trajectory cluster. The resulting contrasts were adjusted for multiple testing using Tukey's method. For each cluster and month pair, the direction of a significant difference was determined from the sign of the test statistic. If the adjusted p-value was below 0.05 and the test statistic was positive, the first month in the comparison was classified as having a significantly higher occurrence probability of the respective cluster. If the adjusted p-value was below 0.05 and the test statistic was negative, the second month was classified as having the significantly higher occurrence probability. Non-significant comparisons were assigned a value of zero.

3. Results

3.1 Temporal distribution of “dust days”

The monthly number of dust days varied substantially over the observation period, ranging from one to ten days per month (Fig. 3 and Fig. 6). Dust-day occurrence was relatively high between January and June 2024, with a minimum of six dust days recorded in May and a maximum of ten dust days in February. In contrast, the period from July 2024 to February 2025 was characterised by generally lower dust-day occurrence frequencies, with the highest number of five dust days during this interval occurring in November 2024 and a minimum of one dust day in July 2024. Overall, months within the main dust season from March to May tended to show slightly higher numbers of dust days detected at three or more stations compared to the off-season, although this pattern was strongly dependent on the respective year (Fig. 6b). In addition, the station-averaged daily mean aerosol concentrations showed somewhat broader variability during the dust season, indicating a wider spread of daily aerosol conditions in these months (Fig. 6a).



As July to September 2025 did not match the requirements for any dust day, these months were not taken into account in the following analyses.

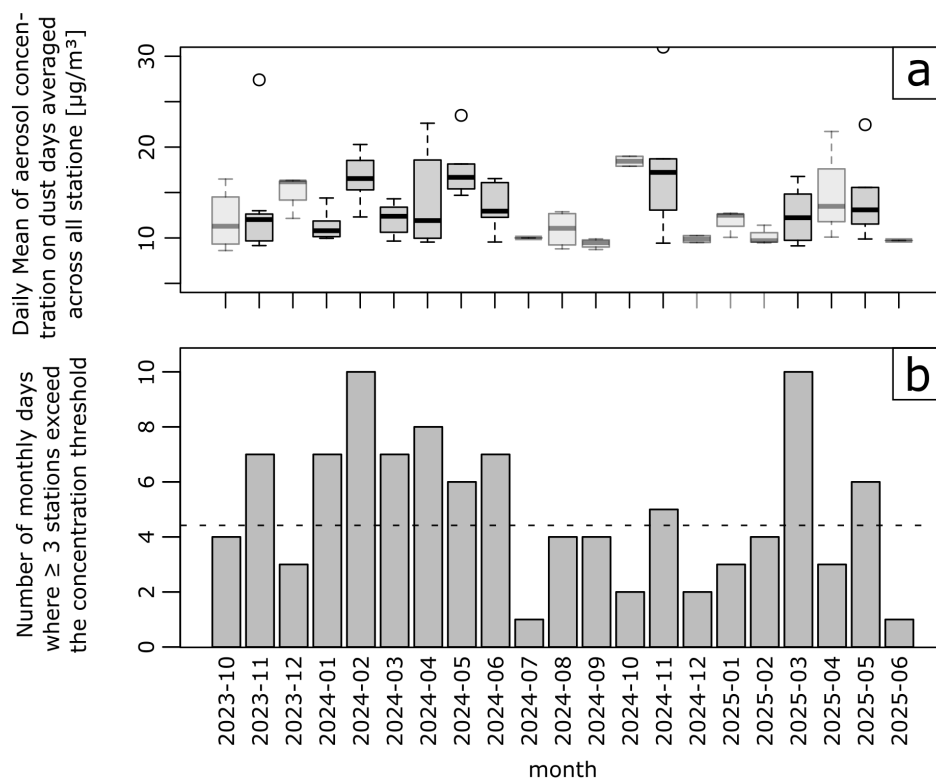


Figure 6: a – monthly grouped daily means averaged across stations. Boxplots in lighter grey indicate limited reliability due to low number of values ($n < 5$); b – monthly grouped number of days on which ≥ 3 stations exceeded a daily mean of $8.16 \mu\text{g}/\text{m}^3$.



3.2 Trajectory modelling

3.2.1 Trajectory modelling

The simulated 96 h backward trajectories show a broad spatial distribution pattern around Crete, indicating that air masses reaching the station at Agios Ioannis Sfakion followed highly variable transport pathways before the arrival in the identified dust days (Fig. 7). Trajectories extend across large parts of the Mediterranean region and beyond, but several areas are only

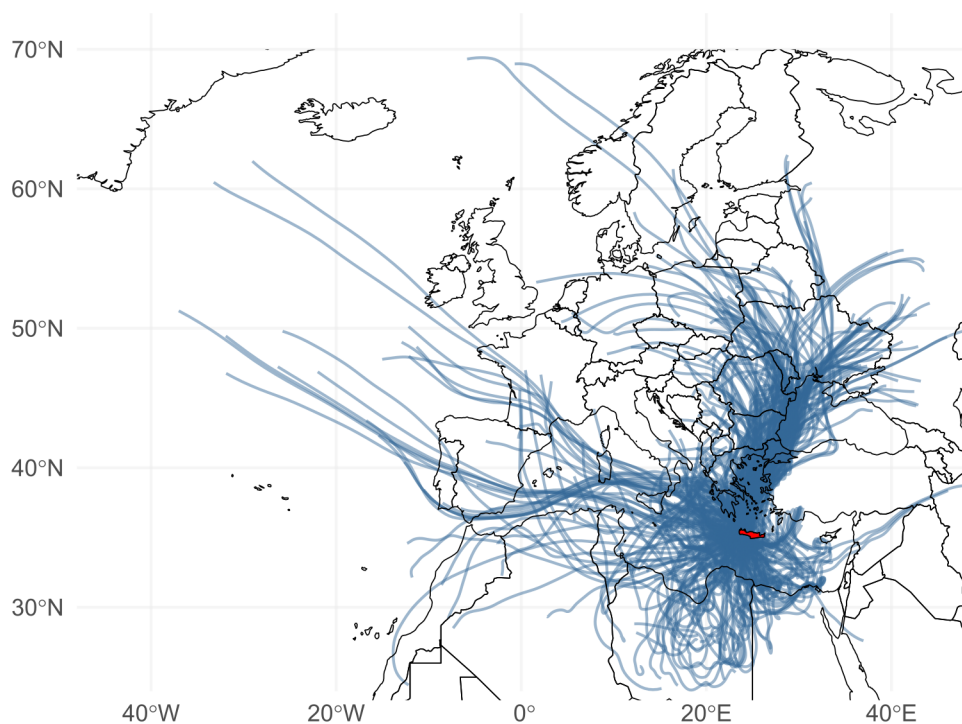


Figure 7: HYSPLIT backwards trajectories for Agios Ioannis Sfakion for all dust days between 2023-10 and 2025-09. Four trajectories for each dust day (00:00, 06:00, 12:00, 18:00). Trajectories were calculated for 96 h before arrival on surface level based on NCEP/NCAR Reanalysis dataset (Kalnay et al. 1996).

barely crossed. In particular, the region northeast of Crete towards Turkey as well as areas east of Crete, are barely covered by any trajectory during the observation period. Similarly, a distinct corridor with a very limited number of dust trajectories is visible over large parts of Italy and further towards the northwest, especially north of Apulia. The total distance travelled during the 96 h before arrival at Agios Ioannis Sfakion on Crete differs markedly between trajectories. While air masses originating from the North Atlantic sector travelled distances of up to 5,000 km, several trajectories approaching Crete from Libya and Egypt covered substantially shorter distances, in some cases less than 1,000 km.

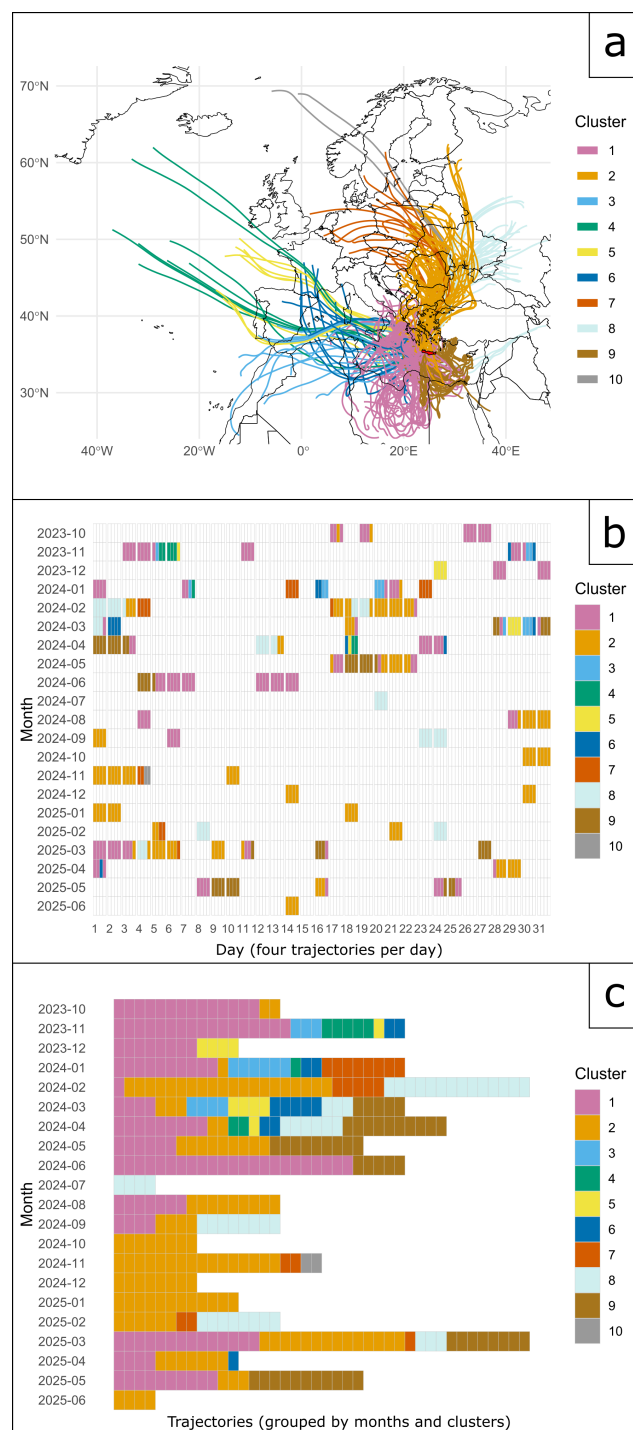


Figure 8: a – Hierarchically clustered backwards trajectories based on Fréchet distances (10 clusters); b – chronological cluster affiliations of trajectories of dust days; c – monthly grouped number of trajectories and cluster affiliations.

3.2.2 Cluster analysis of trajectories

The trajectory cluster analysis shows a strongly uneven distribution of trajectory affiliations among the ten clusters (Fig. 8a). Altogether, clusters 1, 2, 8, and 9 dominate, containing between 46 and 131 trajectories each, whereas all remaining clusters include only 18 trajectories or less (Fig. 9). Clusters 2, 7, 8, and 10 comprise trajectories approaching Crete from northerly directions, although their locations 96 h prior to arrival are widely dispersed, extending from the North Sea to western Russia. In contrast, clusters 3, 4, 5, and 6 include trajectories arriving from the west, partly following pathways along the North African coast and/or across the western Mediterranean before reaching Crete. Their 96 h starting points range from the Azores to the North Atlantic west of Iceland. Clusters 1 and 9 are almost exclusively composed of trajectories approaching from the southwest to southeast and mainly cover the eastern Mediterranean, Libya, and Egypt.

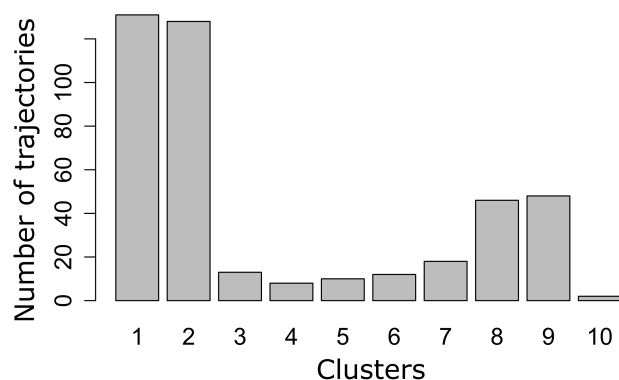


Figure 9: Histogram of cluster affiliations.

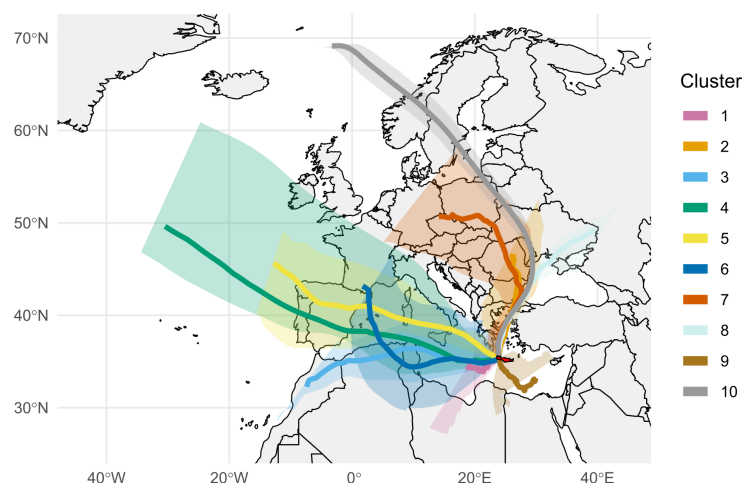


Figure 10: Cluster-wise median trajectories with an envelope representing the 10th and 90th percentile in the respective cluster.

Thus, exceedances of the aerosol concentration threshold identified in this study were most frequently associated with air masses arriving either from the southern sector, between the southeast and southwest, or from northerly directions. The cluster-wise median trajectories, including the 10th to 90th percentile range, further illustrate the main transport corridors represented by each cluster and show that the more frequent cluster affiliations originate from a comparatively limited part of the mapped domain (Fig. 10). A monthly overview of the number of dust days grouped by cluster affiliations provides both, a summary of the temporal distribution of threshold exceedances and an indication of how the relative importance of individual trajectory clusters varied over the observation period and throughout the year (Fig. 8b and 8c).

The cluster-specific dust concentrations measured at Agios Ioannis (Fig. 11) show that two of the four westerly clusters (4 and 6) have the highest median concentrations of all clusters with 14.0 and 13.8 $\mu\text{g}/\text{m}^3$ respectively. This is consistent with the high dust concentrations associated with transport by Sharav cyclones. However, as the number of concentration values that went into the calculation of the boxplots is only a fourth of the number of the quarter daily trajectories (see ‘n’ in Fig. 11), the boxplots for clusters 4 and 6 is too low to allow for a meaningful representation of the distribution. A similar limitation applies

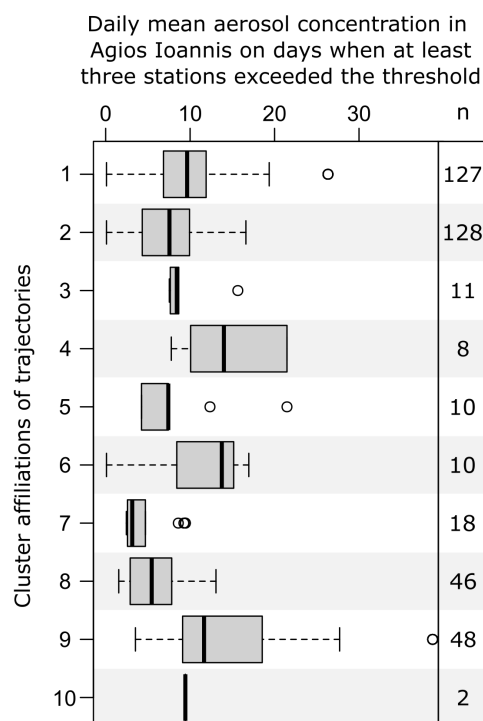


Figure 11: Cluster-wise distribution of daily mean aerosol concentrations in Agios Ioannis Sfakion on dust days; n – number of quarter daily trajectories assigned to the respective clusters.



320 to clusters 3, 5, 7, and 10. The more frequent clusters 1, 2, 8, and 9 show lower median concentrations, ranging from 5.5 to 11.7 $\mu\text{g}/\text{m}^3$. Clusters 1 and 9, which comprise trajectories arriving from southerly directions, show concentration distributions with markedly higher daily mean values, reaching up to 19.4 and 27.7 $\mu\text{g}/\text{m}^3$, respectively, after excluding extreme values, compared with clusters 2 and 8, for which the corresponding maximum values are 16.6 and 13.1 $\mu\text{g}/\text{m}^3$.

3.2.3 Pressure composites

325 The composite plots of median sea-level pressure and associated anomalies show the average pressure conditions typical for each cluster, which result in the corresponding trajectories. Thus, the composite plots reveal distinct synoptic-scale circulation patterns representative for the main trajectory clusters at the time of arrival at Agios Ioannis Sfakion (Fig. 12a). Trajectories from clusters 4, 5, and 10 occur only on five days or less during the observation period and are therefore not suitable to calculate meaningful composites and are not considered here. The most frequently observed clusters, particularly clusters 1, 2, 8, and 9
330 (Fig. 9) differ markedly in their pressure patterns over the Mediterranean basin and the adjacent regions.

Cluster 1 is characterized by a comparatively weak pressure gradient over the eastern Mediterranean at the time of arrival (Fig. 12a₁). While regions of higher pressure are evident over the subtropical North Atlantic and around the Caspian Sea, cluster-specific low-pressure areas are mainly located over northwestern Europe. This suggests that dust-day trajectories assigned to cluster 1 occurred under relatively weak pressure gradients across the Eastern Mediterranean, with the main
335 synoptic-scale pressure gradients situated farther to the north and west of the study area.

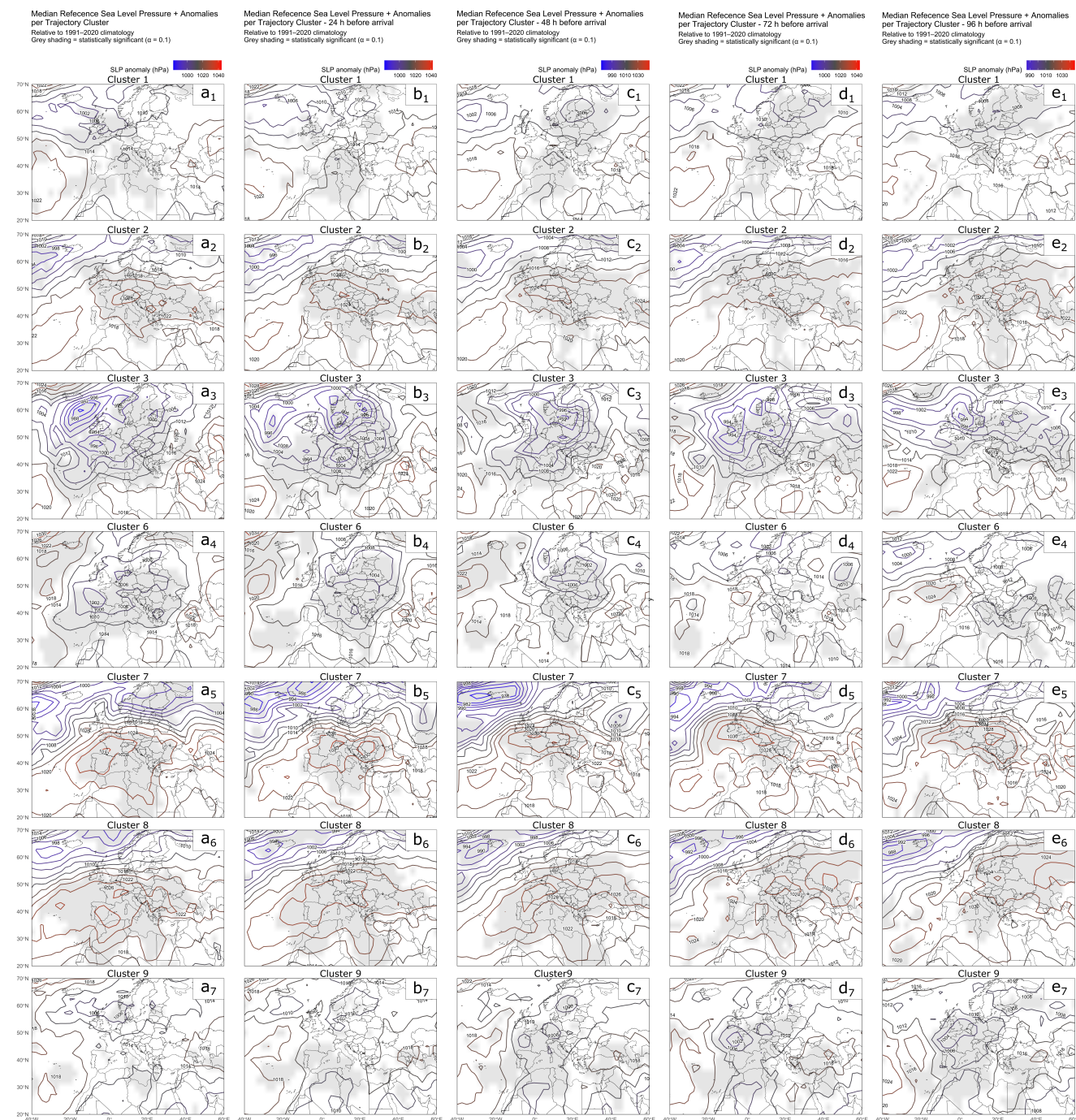


Figure 12: Composite-plots representing typical cluster-wise sea level pressure distributions; rows – different clusters; columns – different time steps (f.l.t.r. time of arrival, 24, 48, 72, 96 h before arrival).



Cluster 2 shows a pressure pattern characterized by more pronounced gradients. At the time of arrival, a high-pressure system extends across large parts of central and eastern Europe, the Balkans, and the eastern Mediterranean, while lower pressure is present over the North Atlantic and northern Europe (Fig. 12a₂). This configuration produces a marked north south pressure contrast and is consistent with the northerly trajectory pathways represented by this cluster. Thus, elevated aerosol concentrations associated with cluster 2 occurred under conditions where the eastern Mediterranean was under the influence of relatively high pressure, while low-pressure systems were positioned farther to the north.

A similar but even more pronounced anticyclonic influence is evident for cluster 8. The arrival-time composite shows a widespread high-pressure system over North Africa, the central and eastern Mediterranean, southeastern Europe, and parts of western Asia (Fig. 12a₆). The center of this high-pressure system lies between Northwest Africa and France. In contrast, low-pressure systems are located over the North Atlantic and northern Europe. This indicates that cluster 8's dust days were associated with strong pressure gradient between the Mediterranean region and northern Europe, fostering air-mass transport towards Crete from northern sectors.

Cluster 9 differs from clusters 2 and 8 by showing a in general less pronounced pressure gradient (Fig. 12a₇). While an area of low pressure is centered over northern and northwestern Europe, high-pressure systems are located over the eastern North Atlantic along the Moroccan coast. Together with the trajectory-cluster pattern, this indicates that cluster 9 represents dust-day situations during which air masses approached Crete predominantly from the southern to southeastern sectors, but without any strong pressure gradient nearby Crete.

Overall, the arrival-time composites show that most frequent dust-day trajectory clusters are associated with two general types of synoptic patterns. Clusters 2 and 8 are linked to a stronger pressure gradient with high pressure over the Mediterranean extending across southern and southeastern Europe, consistent with northerly transport pathways towards Crete. In contrast, clusters 1 and 9 show weaker pressure gradients over the eastern Mediterranean and less spatially coherent pressure differences near Crete. These patterns suggest that elevated aerosol concentrations on Crete can occur under different synoptic circulation patterns, with both northerly transport under anticyclonic Mediterranean conditions and southern-sector transport under weaker regional pressure gradients contributing to the identified dust-day record. Cluster 2 and cluster 8 show significance in the areas of high and low-pressure systems, while the areas of indicated significance of the cluster-specific sea-level pressure in cluster 1 and cluster 9 are generally smaller in size and more fragmented.

The large-scale pressure patterns at 24, 48, 72, and 96 h before the arrival of the air masses already show a similar picture of the general weather situation (Fig. 12b-12e).

3.2.4 Regression analyses

The pairwise monthly comparison of trajectory-cluster affiliations at Agios Ioannis Sfakion shows that significant differences in the modelled probability of cluster occurrence are concentrated in a limited number of clusters (Fig. 13). The strongest month-to-month contrasts are observed for clusters 1, 2, 8, and 9, whereas clusters 4, 5, 6, 7, and 10 show no significant differences between months and are therefore not displayed in Fig. 13. Cluster 3 (also not shown) displays only an isolated



370 significant contrast, indicating that most of the temporal variability in trajectory-cluster occurrence is associated with the dominant trajectory groups.

Cluster 1 shows a heterogeneous pattern of significant monthly differences (Fig. 13a), with both row-dominant and column-dominant months occurring throughout the observation period. This indicates that the occurrence probability of this cluster changed over time, but without forming one simple seasonal block. Still there are two periods with continuously significantly
 375 higher probability for trajectories to be affiliated with cluster 1. October 2023 to January 2024 show significantly more occurrences of cluster 1 as well as March and May 2025.

Cluster 2 exhibits a more structured pattern (Fig. 13b). The months between October 2024 and January 2025 show significantly higher occurrence probabilities relative to multiple other months. Note that October 2023 to January 2024 do not show the same pattern. In addition, June 2025 stands out through a large number of significant contrasts, indicating an enhanced relative
 380 contribution of this cluster during this month. The pattern suggests that cluster 2 was not evenly distributed across the observation period, but instead became particularly relevant during specific phases.

Cluster 8 also shows numerous significant month-to-month differences (Fig. 13c). The contrasts are arranged in distinct horizontal and vertical bands, indicating individual months differed systematically from a larger set of other months. This pattern suggests pronounced temporal variability in the occurrence of cluster 8, with certain months showing clearly enhanced
 385 or reduced probabilities relative to the rest of the record. Especially February, July, and September 2024, as well as February 2025 show enhanced probabilities. Compared to the rarer clusters, the number of significant contrasts indicates that cluster 8 represents a temporally variable but statistically well-resolved component of the trajectory dataset.

Cluster 9 shows a similarly pronounced temporal structure, with several significant contrasts concentrated around spring and early summer months (Fig. 13d). In particular, April and May 2024 and May and June 2025 differ significantly from a broad
 390 range of other months, indicating that the probability of cluster 9 occurrence was elevated during these periods. This is consistent with the importance of this cluster for dust-day trajectories approaching Crete from the southern to southeastern sector.

Overall, the regression-based monthly comparison indicates that the temporal variability of trajectory-cluster occurrence at Agios Ioannis is mainly driven by clusters 1, 2, 8, and 9. The remaining clusters contribute only minor or statistically weak
 395 temporal signals. Since the analysis treats each year-month separately, the results highlight variability between individual months of the observation period rather than a purely climatological seasonal cycle. A longer observation period would be necessary to meaningfully analyse the annual cycle and to draw statistically robust conclusions on trajectory-cluster occurrence probabilities that are independent of individual years.

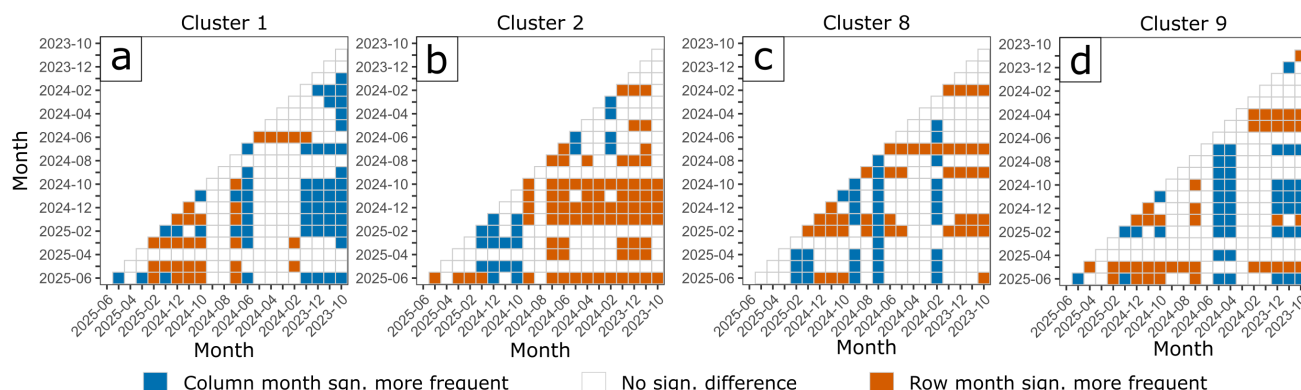


Figure 13: Pair-wise post-hoc comparison of multinomial logistic regression analysis, showing significant differences in the occurrence probability of the different clusters.

4. Discussion

4.1 Dust-Day Distribution

The monthly distribution of dust days observed between October 2023 and September 2025 is broadly consistent with previous studies identifying spring as the main period of enhanced dust transport in the eastern Mediterranean (Gkikas et al. 2013; Israelevich et al. 2012; Varga et al. 2014). During the observation period, monthly dust-day numbers ranged between 0 and 10 (Fig. 6b), and our dataset includes two dust seasons from March to May (Israelevich et al. 2012; Kalivitis et al. 2007). This seasonal framing agrees with earlier satellite-, trajectory-, and surface-measurement based studies, which show that dust transport over the eastern Mediterranean is particularly active in spring (Gkikas et al. 2013; Israelevich et al. 2012; Nihlén et al. 1995; Varga et al. 2014).

At the same time, the observed dust-day distribution also illustrated that the spring maximum should not be interpreted as a temporally uniform or annually stable feature. In 2024, dust-day numbers during the dust season were consistently above the monthly average, whereas April 2025 showed a comparatively low number of only three dust days. This interannual contrast is in line with previous work emphasizing the high temporal variability of Mediterranean dust transport, which depends strongly on the occurrence, position, and intensity of suitable synoptic circulation patterns rather than on calendar season alone (Dayan et al. 2008; Gkikas et al. 2013; Israelevich et al. 2012; Varga et al. 2014). A longer observation period would therefore be required to determine whether the differences between the two observed dust seasons represent statistically robust interannual variability or merely reflect the short-term variability of individual dust transport events.

The concentration distribution further suggests that dust-day frequency and dust-event intensity are not necessarily equivalent indicators. Median aerosol concentrations on dust days during the main dust season do not show strongly pronounced positive deviations compared with the off-season distribution (Fig. 6a). However, the dust-season distribution occasionally exhibits substantially larger variability than those of other months. This pattern is consistent with the idea that spring provides favourable conditions for both frequent and potentially intense long-range dust transport, while individual event intensity



remains controlled by event-specific meteorological conditions. Conversely, the more homogeneous off-season dust-day concentrations indicate that dust transport outside the main spring period may still occur, but tends to be associated with less variable and generally less intense aerosol loading. This is also compatible with earlier studies reporting additional, weaker dust-activity periods in summer and autumn for parts of the eastern Mediterranean, although spring remains the dominant season for strong dust transport (Israelevich et al. 2012; Kubilay et al. 2003; Papanastasiou et al. 2010).

4.2 Cluster Analysis

The trajectories and clusters of the dust days can be broadly divided into three groups. Trajectories assigned to clusters 2, 7, 8, and 10 approach Crete from northerly directions, whereas clusters 1 and 9 comprise trajectories from the southern sector or the immediate surroundings of western Crete, and clusters 3, 4, 5, and 6 include trajectories arriving from the west (Fig. 8a). In total, 353 out of 416 trajectories from 104 dust days, corresponding to 15% of all days during the observation period, are assigned to clusters 1, 2, 8, and 9 (Fig. 9). By contrast, the clusters representing westerly transport pathways contain only a small number of trajectories, with eight to 11 trajectories each (Fig. 11). These westerly clusters are particularly relevant because their pathways broadly correspond to the transport route of dust brought into the eastern Mediterranean by Sharav cyclones during the main dust season from March to May (Flaounas et al. 2015; Israelevich et al. 2002). Our results do not contradict this interpretation, but rather suggest that large dust loads are transported to western Crete during a limited number of major events, and that even during the main dust season dust transport is not continuous. The monthly distribution of cluster affiliations during the observation period (Fig. 8c) shows a high variability among clusters, particularly during the 2024 dust season. This variability may contribute to the broader spread in aerosol concentrations observed on dust days during these months, as discussed above. The provenance shifts can occur very rapidly and even consecutive quarter-daily trajectories may indicate provenance regions from opposite directions (Fig. 8b e.g. May 2024 and March 2025).

When combining information on cluster frequency (Fig. 9) with the cluster specific concentration distributions (Fig. 11) regarding the maximum values, clusters 1 and 9 can be considered the most likely dominant trajectory clusters contributing to the overall dust load in western Crete and the eastern Mediterranean region.

4.3 Pressure Composites

When focusing again on the four most frequent clusters in the composite plots representing the typical cluster-specific pressure conditions, clusters 1 and 9 show a smaller spatial extent of statistically significant pressure values (Fig. 12). The number of values included in the composites does not appear to be the decisive factor, as at least clusters 2 and 8 occur with comparable frequency (Fig. 11), yet exhibit substantially larger areas covered by significant values. This suggests that clusters 2 and 8 are associated with more pronounced cluster-specific deviations in the pressure field relative to the climatology of the corresponding days.

The cluster-specific sea-level pressure composites provide a synoptic context for the contrasting transport pathways represented by the trajectory clusters. Clusters 1 and 9 are dominated by air masses approaching Crete from the southern sector,



455 whereas clusters 2 and 8 mainly represent northerly transport towards the island. These differences are broadly consistent with the corresponding pressure patterns at the time of air-mass arrival.

For clusters 1 and 9, the composite sea-level pressure fields show comparatively weakly structured pressure patterns over the eastern Mediterranean, with lower pressure situated farther north to northwest over Europe and higher pressure generally present towards the subtropical North Atlantic, North Africa, and parts of the eastern Mediterranean (Fig. 12a₁ and Fig. 12a₇).
 460 The resulting atmospheric circulation pattern places Crete within a southerly to southwesterly air flow, which suggests a direct connection to potential North African dust source regions, particularly in Libya and Egypt. Similar south-to-north and eastwards dust transport pathways towards the eastern Mediterranean have been described for Sharav cyclone-related transport and for dust events observed over Crete (Israelevich et al. 2002; Kalivitis et al. 2007; Fiedler et al. 2014).

In contrast, clusters 2 and 8 are associated with a more pronounced anticyclonic circulation pattern over the Mediterranean
 465 and southern to southeastern Europe. At the time of arrival, sea-level pressure is high over the eastern Mediterranean, while lower pressure occurs farther north and northwest over northern Europe and the North Atlantic (Fig. 12a₂ and Fig. 12a₆). The resulting atmospheric circulation pattern leads to northerly to northwesterly air mass advection towards Crete, and is similar to the pressure-gradient-driven Meltemi/Etesian wind circulation described for the eastern Mediterranean (Tyrlis and Lelieveld 2013; Misios et al. 2022; Tyrlis et al. 2013). The comparison of these cluster-specific pressure patterns highlights that elevated
 470 aerosol concentrations at Crete occurred under more than one synoptic regime.

Comparison of the cluster-specific composite plots with the monthly climatology (Fig. S4) shows that clusters 1 and 9 most closely resemble the monthly median pressure patterns of April and May which are characterized by a weak Icelandic Low and a weak Azores High, but otherwise only a very limited pressure gradient. In contrast, clusters 2 and 8 exhibit pressure patterns more similar to those observed between October and January, including a more pronounced Icelandic Low and a high-
 475 pressure belt extending from the Azores across the Mediterranean region towards western Asia.

4.4 Cluster Occurrence Distribution

This relationship between seasons and clusters is also reflected to a large extent in the monthly distribution of trajectory-cluster affiliations (Fig. 8c), but becomes particularly evident from the multinomial regression analysis and the pairwise comparisons of monthly cluster occurrence. Especially for clusters 2 and 9, the results statistically confirm that these clusters occur
 480 significantly more frequently during those parts of the year in which the cluster specific pressure patterns resemble the corresponding patterns of the monthly climatology. Therefore, cluster 2 occurs significantly more frequently between October 2024 and January 2025 than in most other months. Cluster 8, by contrast, does not show a continuous period of significantly enhanced occurrence except for January to February 2025. Cluster 9 closely matches the expectation derived from the comparison between the composite plots and the monthly climatology in April and May 2024, when it occurs significantly
 485 more frequently than in almost all other months. In the following year, this period is shifted by approximately one month, with May and June 2025 standing out significantly. Cluster 1 shows a similar pattern as cluster 9 in 2025 and additionally a strong occurrence in March 2025, but does not exhibit a distinct signal during the corresponding period in 2024, except for June.



However, the period from October 2023 to January 2024 is notable, as cluster 1 occurs significantly more frequently than, for example, during the same period in the following year. During this phase in 2023/2024, cluster 1 is dominant and is accompanied by all clusters representing westerly trajectories, whereas cluster 2, which becomes clearly dominant during the same seasonal phase in 2024/2025, occurs only sporadically in October and January (Fig. 8c).

These results indicate pronounced interannual variability in the seasonal occurrence of trajectory clusters. Therefore, extending the observation period would be useful for deriving more robust and statistically reliable conclusions regarding the interannual seasonal distribution of transport pathways towards Crete.

4.5 Conclusive Discussion

According to the current state of research, the main source of dust reaching the eastern Mediterranean is North Africa (Dayan et al. 1991; Ganor and Mamane 1982; Israelevich et al. 2002; Kubilay et al. 2000; Moulin et al. 1998). This is mainly due to its geographical proximity and to large-scale atmospheric circulation patterns that favour dust mobilization and transport, at least during certain parts of the year (Moulin et al. 1998; Fiedler et al. 2014; Flaounas et al. 2015; Kalivitis et al. 2007). In a more detailed assessment of the dominant potential source areas, Bitzan et al. (2026a) analyse the seasonal evolution of dominant source regions for deposited dust in western Crete based on mineralogical and isotopic signatures. Their results indicate a seasonal shift of dominant source regions along the North African coast, from eastern Algeria and Tunisia towards Libya and central Egypt. Based on the mineralogical composition and isotopic signature of the deposited material, Libya appears to represent the most important source region for dust transport to western Crete.

This dominant source region is represented by clusters 1 and 9 identified in this study, with the strongest spatial overlap in Libya and western Egypt (Fig. 8a). These two clusters are among the most frequently occurring clusters and, among those frequent clusters, include the trajectories of days on which the highest aerosol concentrations were measured (Fig. 11). This supports the identification of clusters 1 and 9 as key dust-season clusters. The temporal classification of the dominant source regions in Bitzan et al. (2026a), which corresponds closely to the trajectories assigned to cluster 1, is also consistent with the results of the composite plots (Fig. 12). These show that days with trajectories assigned to cluster 1 are associated with pressure conditions resembling the typical circulation patterns of spring to early summer (Fig. 12a₁ and Fig. S4).

Clusters 2 and 8, on the other hand, indicate northerly to northeasterly transport pathway linking Crete to continental source regions over the Balkans, western Turkey, the Black Sea region and eastern Europe. While these regions are not generally considered dominant mineral dust sources for the eastern Mediterranean in the same way as North Africa (Moulin et al. 1998; Fiedler et al. 2014; Flaounas et al. 2015), previous studies have shown that they can contribute to the aerosol chemical composition in the region and may act as episodic sources of resuspended soil or agricultural dust (Güllü et al. 2005; Doğan et al. 2008; Dimitriou et al. 2022). However, the results of this study show that almost 50% of the dust days according to our definition are associated with trajectories from these regions. Birmili et al. (2008) demonstrated that, for example, southern Ukraine can act as a source of mineral dust. In combination with the trajectories assigned to the corresponding clusters, this suggests that such regions may also influence dust transport to western Crete. Although the associated concentrations do not



reach the magnitude of major dust events originating from North Africa, the sheer frequency of their occurrence argues for greater consideration of these regions in research on dust-source areas affecting the eastern Mediterranean.

5. Conclusion

Combining aerosol concentration measurements in deposition areas with backward-trajectory modelling allows trajectories to be filtered and thereby enables the exclusive consideration of transport pathways associated with elevated aerosol concentrations and, potentially enhanced dust deposition. Although this approach does not allow the relative contributions within mixed samples to be quantified, it provides a much more detailed differentiation of potential contributing provenances than can be achieved by considering mineralogical and isotopic compositions alone, where sources with larger contributions may mask weaker source signals. In addition, it enables a substantially higher temporal resolution of provenance assessment as it is not dependent on the availability of a minimum amount of deposited sample material. This approach additionally shows that also short periods of time and even the same dust event in the deposition region can be fed from multiple sources from different continents.

Overall, the results obtained from the combined analysis of concentration measurements and trajectory modelling are largely consistent with provenance analyses based on the isotopic and mineralogical composition of dust samples from deposition areas. However, the higher temporal resolution reveals additional source regions that likely contribute substantially less to the depositional dust load and deviate from the most frequently identified dominant sources. Thus, rather than narrowing the seasonal source regions more precisely than laboratory-based analyses of deposited material, this approach expands the range of potential contributing regions, thereby improving the accuracy of seasonal source attribution. The results further indicate that the distribution of different provenances may vary noticeably between years.

In addition to the source regions in North Africa, this study highlights the relevance of often underrepresented sources from eastern Europe. Although the concentrations associated with these provenances are lower than those linked to North African transport, their frequent occurrence suggests that they should at least be considered as potential contributors of aerosol admixtures to dust samples in the eastern Mediterranean region.

The temporally highly resolved assessment of trajectories on days with elevated dust concentrations in western Crete further shows that seasonally dominant source regions, particularly during the main dust season, are accompanied by additional dust-bearing trajectories from other source areas. This implies that mixed deposition may occur even over relatively short time intervals. Consequently, dust transport during the main dust season should not be interpreted as a continuous flux from the dominant source region with only varying intensity, but rather as an intermittent process that is frequently interrupted or accompanied by contributions from weaker additional sources.

The comparison with cluster-specific sea-level pressure composites further supports the interpretation of distinct transport regimes. Southern-sector clusters are associated with pressure configurations resembling spring to early-summer circulation patterns, whereas the northern clusters correspond more closely to pressure fields typical of autumn and winter, characterized



by stronger anticyclonic influence over the Mediterranean and southeastern Europe. These results indicate that the temporal distribution of dust-source regions is closely linked to season-specific atmospheric circulation patterns, but also shows marked interannual variability.

Future work should extend the observation period to improve the statistical robustness of seasonal and interannual patterns. Combining trajectory filtering with chemical mineralogical, isotopic, and deposition-flux measurements could allow the relative contribution of individual source regions to be quantified more directly if the sample sizes are big enough. Additional information from satellite observation, vertical aerosol profiles, and wind fields at different atmospheric levels could further improve the interpretation of dust transport pathways and their role in dust deposition across the eastern Mediterranean.

Code and data availability

Figures were made in R version 4.3.3 (R Core Team 2024). Data regarding the daily means of the OPC-measurements are available in Bitzan et al. (2026b). The NCEP/NCAR reanalysis data is made available by NOAA ARL (2026). Trajectories were computed using the HYSPLIT Lagrangian model (Stein et al. 2015). Data on relative humidity for OPC-data filtering was provided by the National Observatory of Athens/meteo.gr. The code for statistics and figures will be provided upon request.

Author contributions

Simon Bitzan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft. **Fabian Kirsten:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Kerstin Schepanski:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing

Competing interests

The authors declare that they have no known competing financial interests or personal relationship that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the National Observatory of Athens/meteo.gr, for providing the meteorological data. We gratefully acknowledge Michaelis Polychronakis for his support with maintenance of the monitoring stations, as well as for his valuable contribution to the conceptual development of the station set-up. We also thank Haritos Bobolakis, Georgios and



580 Ines Zafirakis, Andreas and Kaliopi Meladakis, Ieronimos Gialledakis, Antonis and Anna Georgedakis, Thanasis Fytorakis, and Georgios Drakoulakis for allowing us to install the monitoring stations on their roofs or properties and for generously providing electricity, Wi-Fi, hospitality, and many delicious treats. We are also grateful to Leandros Symeonidis for providing contact information and for his trust and support. Furthermore, we thank Benjamin Rommel for his assistance in implementing the optical particle counters at Freie Universität Berlin. Open Access funding was enabled and organized by Project DEAL.

585 **Financial support**

This research was funded by the Research Committee of the Freie Universität Berlin.

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