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ORIGINAL PAPER

Spatiotemporal variation and long-range transport of *Alternaria* and *Cladosporium* spores in a bowl-shaped basin of Eastern Anatolia (Türkiye)

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Abstract Spores of *Cladosporium* and *Alternaria* are significant airborne allergens and major agricultural pathogens. This study evaluates the seasonal, intra-diurnal, and transport-related dynamics of these taxa over a two-year period (2018–2019) in Bingöl, eastern Anatolia. Atmospheric sampling was conducted using a Hirst-type volumetric trap, and the influence of meteorological factors and air mass transport was assessed using statistical analyses and HYSPLIT back-trajectory modeling. *Cladosporium* was approximately four times more abundant than *Alternaria*, and both taxa exhibited peak concentrations in May. *Alternaria* exceeded the clinical allergy threshold (100 spores/m^3) on six days, whereas *Cladosporium* remained below its critical threshold (3000 spores/m^3) throughout the study period. Mean temperature was identified as the primary meteorological driver of spore concentrations, and a significant delayed response to precipitation was observed, with concentrations increasing following a 1–3-day lag. A clear intra-diurnal pattern was observed, with *Alternaria* peaking in the morning predominantly under northerly winds, whereas *Cladosporium* reached maximum levels in the afternoon mainly under southerly air masses. HYSPLIT analysis indicated that peak episodes were associated with air masses originating from the southern sector, particularly over the Mesopotamian plains. An anomalous early-season peak of *Alternaria* in February, occurring during periods of local dormancy and snow cover, was associated with air masses originating from the southern sector. Vertical trajectory profiles showed that air masses approached the study area at low altitudes with a consistent descending pattern. These findings highlight the combined influence of local meteorology, basin morphology, and regional air mass transport on airborne spore dynamics.

Keywords Airborne fungal spores · Aeromycology · Allergy · Biomonitoring · Meteorological parameters · Seasonal dynamics

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1 Introduction

Fungal spores constitute a significant portion of bioaerosols in the atmosphere (Haas et al., 2023). Although they are present in the air year-round, their

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atmospheric concentrations vary seasonally, and fluctuate throughout the day (Oliveira et al., 2009). These variations are influenced by geographic location, meteorological factors, human activities, and the regional vegetation composition (Adhikari et al., 2016; Anees-Hill et al., 2022). Spores of the genera *Cladosporium* and *Alternaria* are particularly important in aeromycological studies due to their dual relevance to human health and agriculture. They are well-recognized airborne allergens associated with respiratory disorders such as asthma and rhinitis in humans (Bouziane et al., 2005; D'Amato et al., 2007; Filali Ben Sidel et al., 2015; Górzyńska et al., 2023). Furthermore, spores of *Alternaria* and *Cladosporium* also cause significant diseases and economic losses in agricultural products (Ogórek et al., 2012; Skjøth et al., 2016).

Recent studies have shown that the sporulation periods of fungal spores such as *Alternaria* and *Cladosporium* have lengthened due to climate change and shifting meteorological patterns, increasing potential exposure in previously under-monitored regions (Anees-Hill et al., 2022). Therefore, continuous monitoring of fungal spore concentrations remains essential.

Investigations into the temporal and spatial distribution of airborne fungi have been extensively conducted in various regions worldwide (Aira et al., 2012; Akgül et al., 2016; Bednarz & Pawłowska, 2016; Fang et al., 2019; Gioulekas et al., 2004; Grinn-Gofroń et al., 2020; Kallawicha et al., 2017; Kasprzyk et al., 2004; Liu et al., 2019; Reyes et al., 2016; Sevindik & Tosunoglu, 2025). The identification of bioaerosols, such as *Alternaria* and *Cladosporium*, and their regional investigation using atmospheric models, like the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, provide valuable insight for both local and long-range influences on spore concentrations (Sadyś et al., 2015). However, previous studies using HYSPLIT or other trajectory models have largely focused on regions with less complex terrain (Grewling et al., 2022; Sadyś et al., 2015; Uguz, 2025); very few have examined basin-shaped settlements that can act as natural geographic traps for airborne spores. Once dispersed, these fungal spores can remain suspended in the air for periods ranging from a few hours to several days. While *Cladosporium* spores generally increase with temperature, particularly in continental and inland regions compared to coastal areas (Sindt et al., 2016), *Alternaria* dynamics are often more complex and site-specific, highlighting the importance of local environmental conditions (Grinn-Gofroń et al., 2018; Ščevková & Kováč, 2019). Therefore, both the physical structure and geographic location of the studied region, together with meteorological conditions, are important for interpreting fungal spore dynamics.

Although numerous aeromycological studies have been conducted in Europe, significant gaps remain, particularly in certain areas (Oliveira et al., 2009). Understanding the abundance and temporal dynamics of airborne fungal spores, including their seasonal and intra-diurnal variations, is essential for interpreting atmospheric spore patterns and may support the development of predictive approaches (Grinn-Gofroń & Strzelczak, 2008, 2009). However, the development of robust predictive models generally requires longer and more extensive datasets, as spore dynamics are strongly influenced by local environmental and climatic conditions (Ščevková et al., 2026; Vélez-Pereira et al., 2019).

Compared to pollen, atmospheric research on fungal spores is relatively limited. Therefore, more detailed and long-term studies are needed in regions where atmospheric fungal spore concentrations remain undetermined. Eastern Anatolia is one of the least studied regions of Türkiye in terms of aeromycological monitoring, despite its pronounced continental climate and complex topography. Bingöl, situated at the northern terminus of the Mesopotamian plains, represents a unique study area characterized by a bowl-shaped topography surrounded by high mountain ranges. This morphology may facilitate the trapping of airborne particles while being simultaneously influenced by long-range air mass transport from the south. However, empirical data addressing the combined effects of basin morphology, local meteorology, and long-distance influx remain scarce. Therefore, integrated studies of continuous volumetric sampling with atmospheric trajectory modeling are essential to improve our understanding of fungal spore dynamics in such environments.

The objectives of the study are as follows: (1) to characterize the spatiotemporal distribution of *Cladosporium* and *Alternaria* spores in Bingöl (Eastern Türkiye) over a two-year timeframe, (2) to determine

the timing and severity of the main spore season, (3) to monitor intra-diurnal patterns, (4) to investigate the contributions of local, long-range, and specialized transport corridors to observed spore concentration peaks, including anomalous events.

2 Material and methods

2.1 Study area

Bingöl is a city located in the upper reaches of the Euphrates River in Eastern Anatolia (41°20′–39°54′ N, 38°27′–40°27′ E), at an elevation of 1151 m (Fig. 1). Characterized by its rugged terrain, the city is surrounded by mountains with elevations of nearly 3000 m, giving it a bowl-shaped appearance. The plain, situated centrally within the city, is encircled by these mountains (Fig. 1). The pressure differential between the mountains and the plains generates airflow from the mountains toward the plains, resulting in prevailing winds that blow from the N–NNE throughout the province. While drought and heat dominate the summer months, abundant precipitation occurs in spring and autumn. Although the harsh continental climate typical of Eastern Anatolia is somewhat alleviated in the Upper Euphrates region, it is still more severe than in nearby lowland regions. The average annual temperature is 12.2 °C, and the total annual precipitation is 947.6 mm, according to the Turkish State Meteorological Service (mean values for the period 1961–2023).

Bingöl Province, located within the basins of the Aras and Euphrates rivers, contains the largest forested area in Eastern Anatolia. The most prevalent tree and shrub species in these forested regions up to an elevation of 1200 m are oaks. Other naturally occurring tree species include: *Betula verrucosa* Ehrh., *Crataegus monogyna* Jacq., *Elaeagnus angustifolia* L., *Fraxinus excelsior* L., *Juglans regia* L., *Populus alba* L., *Populus nigra* L., *Pyrus salicifolia* Pall., *Salix alba* L., *Ulmus glabra* Huds., *Acer platanoides* L., *Alnus glutinosa* L., *Celtis australis* L., *Crataegus orientalis* Paal. Ex. M. Bieb, *Populus tremula* L., *Sorbus aucuparia* L., and *Sorbus torminalis* L. The shrub species include *Cornus alba* L., *Cotoneaster horizontalis* Decne., *Juniperus horizontalis* L., *Rosa canina* L., and *Tamarix tetrandra* Poll. The forests of Bingöl are generally characterized as sparse, with the flora predominantly consisting of shrubs. Steppes are observed at higher altitudes. Consequently, anthropogenic steppes have become the dominant vegetation in these regions (Ahmet et al., 2016; Mansuroğlu & Dağ, 2016; Özbay et al., 2015). Wheat, barley, clover, paddy, chickpeas, beans, potatoes, vetch, sainfoin, and maize are among the most widely cultivated field crops in Bingöl (Özbay et al., 2015).

2.2 Aeromycological study

In this study conducted in Bingöl Province, atmospheric sampling was performed during 2018–2019 using a Hirst-type particle sampler (Lanzoni VPPS 2000). The device operated continuously and was calibrated to aspirate 10 L/min air in each sampling week, for two consecutive years (from January 1, 2018, to December 31, 2019). Melinex® tape, coated

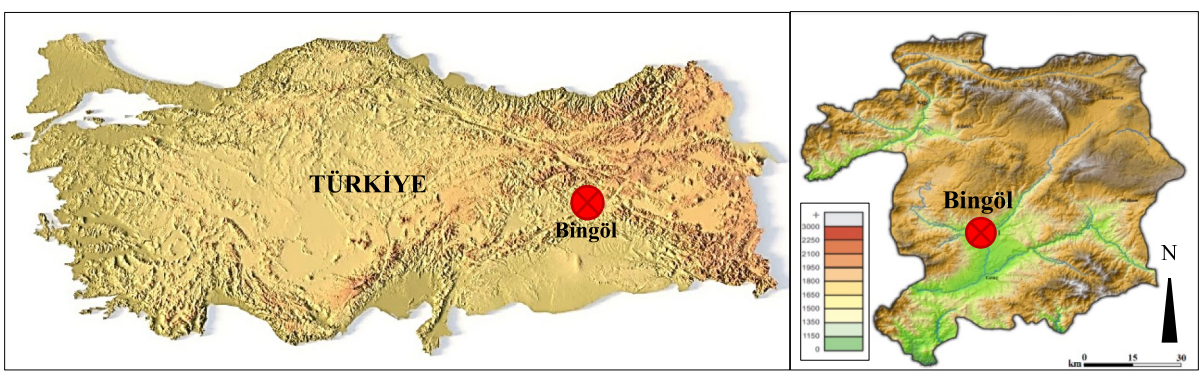


Fig. 1 Location of Bingöl in Eastern Türkiye and the geographic map of Bingöl city

with silicone oil prior to sampling, was removed from the sampling drum along with the adherent atmospheric particles and cut into daily segments. Atmospheric sampling and analyses were carried out as described by the Spanish Aerobiological Network (REA) (Galán et al., 2007, 2014), with modifications that included dividing the slides transversely into 24 intervals instead of 12 and detecting diurnal variations. Spore concentrations were expressed as spores per 1 m^3 of air, according to the technical specification CEN/TS 16868 (European Committee for Standardization, 2015). The start of the Main Spore Season (MSS) is defined by the date by which 5% of the annual spore total is reached, and the end is defined as the date when 95% of the total is accumulated (Nilsson & Persson, 1981). Threshold concentrations triggering allergic symptoms of *Alternaria* and *Cladosporium* spores were set as 100 spores for *Alternaria* and 3000 spores for *Cladosporium* (Gravesen, 1979). These values were used to evaluate days when spore concentrations exceeded allergy-relevant levels during the study.

Within the scope of this study, data were recorded hourly. To categorize the data, the day was first divided into four distinct time periods, similar to methodologies commonly used in pollen research. These periods were defined as follows: night from 00:00 to 06:00, morning from 06:00 to 12:00, afternoon from 12:00 to 18:00, and evening from 18:00 to 00:00. Consequently, the concentration changes of both fungal spores throughout the day were graphed and analyzed on an hourly basis (Tosunoglu & Bicakci, 2015).

2.3 2.3. HYSPLIT back-trajectory analysis and meteorological data

We analyzed peak dates and unusual occurrences of daily spore concentrations, such as the high concentrations of *Alternaria* spores observed at the beginning of 2019, which caused the MSS period to start three months earlier in 2019 than in 2018. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) modeling system (Air Resources Laboratory, 2025) was used to compute 72-h backward air mass trajectories at 1-h intervals (Stein et al., 2015). This approach has also been used in previous studies to identify potential source regions for spores (Fernández-Rodríguez et al., 2015; Grinn-Gofroń et al., 2016; Sadyś et al., 2015).

2.4 2.4. *Statistical analysis*

The meteorological data used in this study were obtained from the Turkish State Meteorological Service and included daily mean temperature, relative humidity, wind speed, and total precipitation. These variables were used to investigate their relationships with airborne fungal spore concentrations of *Alternaria* and *Cladosporium* over the studied period. The normality of the data was assessed using the Shapiro–Wilk test, which indicated a non-normal distribution ($p < 0.05$). Consequently, Spearman's rank correlation analysis was initially performed using raw data to evaluate the relationships between daily spore concentrations and meteorological parameters. The results of this analysis were visualized through a correlation heatmap. To satisfy the assumptions of linear regression (normality and homoscedasticity of residuals), spore concentration data were log-transformed prior to analysis.

To further assess the combined effects of meteorological variables, month, and wind direction on spore concentrations, a multiple linear regression analysis was performed. To identify the most parsimonious set of predictors, an exploratory stepwise multiple linear regression was conducted. For the final optimal models, statistical significance was evaluated at $p < 0.05$. The outcomes of these models were presented in Table 1. All statistical analyses and their visualizations were performed using R software (R Core Team, 2023).

In addition, lagged regression analysis was conducted to evaluate the potential delayed effects of precipitation on spore concentrations, reflecting biological and environmental response times. Precipitation variables with time lags (e.g., 1-day and 3-day lags) were incorporated into the models to determine short-term delayed responses, which were illustrated using regression plots (Fig. 2). Model performance was evaluated using R^2 values.

Table 1 Summary of multiple linear regression analysis for variables predicting $\log_{10}$ transformed daily concentrations of *Alternaria* and *Cladosporium* spores in Bingöl (2018–2019)

Predictors	*Alternaria* (Log)			*Cladosporium* (Log)		
	Estimate	95% CI	*p*-value	Estimate	95% CI	*p*-value
(Intercept)	0.81	[0.05, 1.58]	**0.037**	−0.62	[−1.65, 0.40]	0.232
Meteorological Factors						
Mean Temperature	0.07	[0.05, 0.10]	**< 0.001**	0.04	[0.01, 0.08]	**0.021**
Mean Relative Humidity	−0.00	[−0.01, 0.00]	0.724	0.01	[0.01, 0.02]	**0.001**
Mean Wind Speed	−0.11	[−0.43, 0.20]	0.483	−0.03	[−0.45, 0.39]	0.887
Total Precipitation	−0.01	[−0.02, 0.00]	0.250	−0.01	[−0.02, 0.00]	0.140
Significant Wind Directions						
East–Southeast	0.74	[0.01, 1.46]	**0.047**	1.00	[0.03, 1.97]	**0.044**
Seasonal Effects (Peak)						
May (Month)	0.82	[0.31, 1.34]	**0.002**	2.97	[2.28, 3.66]	**< 0.001**
Model Diagnostics						
Observations	729			729		
R^2/R^2 adjusted	0.40/0.38			0.40/0.37		

Statistically significant values ($p < 0.05$) are highlighted in bold. Only the most representative wind direction and seasonal peak are shown for brevity

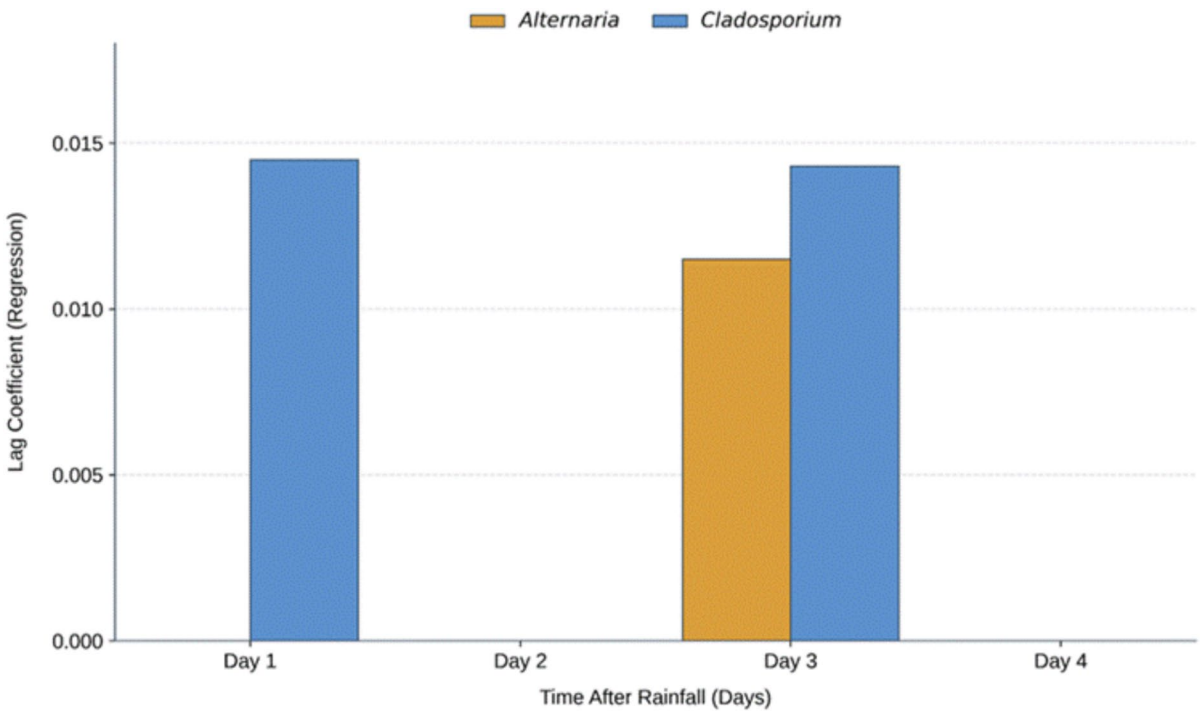


Fig. 2 Lagged regression analysis illustrating the delayed effects of precipitation on *Alternaria* and *Cladosporium* spore concentrations. Bars represent regression coefficients across lag days (1–4 days after precipitation), indicating the magnitude of the lagged response

To investigate inter-annual variations between 2018 and 2019, specific comparative statistical tests were performed. Welch's t-test was applied to compare the inter-annual variations in log-transformed spore concentrations and continuous mean meteorological parameters. Additionally, Pearson's Chi-squared test was employed to evaluate differences in the frequency distributions of categorical wind directions and conditions across different temporal periods (overall hourly, morning, afternoon, and MSS).

All statistical analyses and data visualizations were performed using *R* software (*R* Core Team) along with the packages *dplyr* and *tidyr* for data processing and transformation, *stringr* for text data processing, *ggplot2* for visualization, and the *MASS* and *sjPlot* packages for regression modeling.

3 Results

3.1 3.1. Seasonal and inter-annual variations in spore concentrations

3.1.1 Annual spore loads and taxa distribution

In a two-year study conducted in Bingöl Province, a total of 15,614 spores were recorded in 2018, including 12,290 *Cladosporium* and 3324 *Alternaria* spores. In 2019, a total of 9651 spores were recorded, with 7641 *Cladosporium* and 2010 *Alternaria* spores. Overall, both taxa exhibited a decline in spore numbers, resulting in notably lower total spore concentrations in 2019 compared to 2018. Welch's t-test indicated that spore concentrations were significantly higher in 2018 than in 2019 for both *Alternaria* and *Cladosporium* ($p < 0.05$). In contrast, no significant inter-annual differences were observed in mean meteorological parameters ($p > 0.05$).

3.1.2 Monthly variation and allergy thresholds

Monthly spore dynamics showed that both taxa began to increase in April and reached their main peaks in May in both years (Fig. 3). *Cladosporium* consistently exhibited higher concentrations than *Alternaria* throughout the study period. Following the May peak, concentrations generally declined, with minor secondary increases observed later in the season, particularly in autumn. *Alternaria* showed a less pronounced secondary increase, limited mainly to late summer in 2019.

In 2018, *Alternaria* spores exceeded allergy threshold values on a total of six days (11 May; 13–16 May; 17 June), corresponding to 2.8% of days during the MSS, and in 2019 on two days (6–7 May), corresponding to 1.2% of days. *Cladosporium* spores did

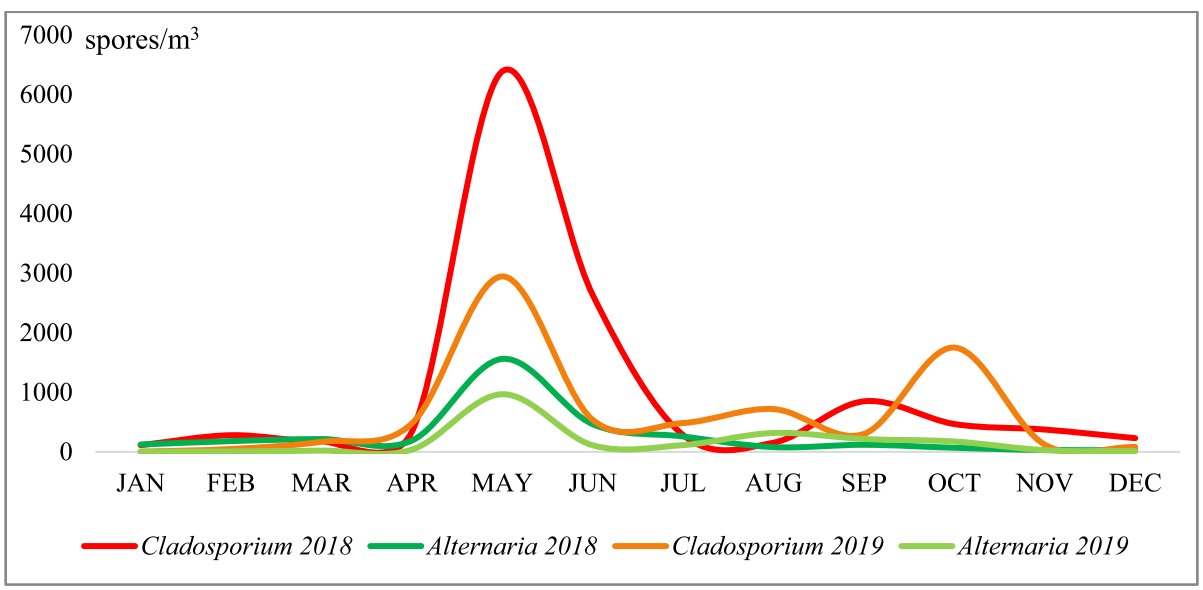


Fig. 3 Monthly distribution of *Cladosporium* and *Alternaria* fungal spores in the Bingöl atmosphere in the studied years

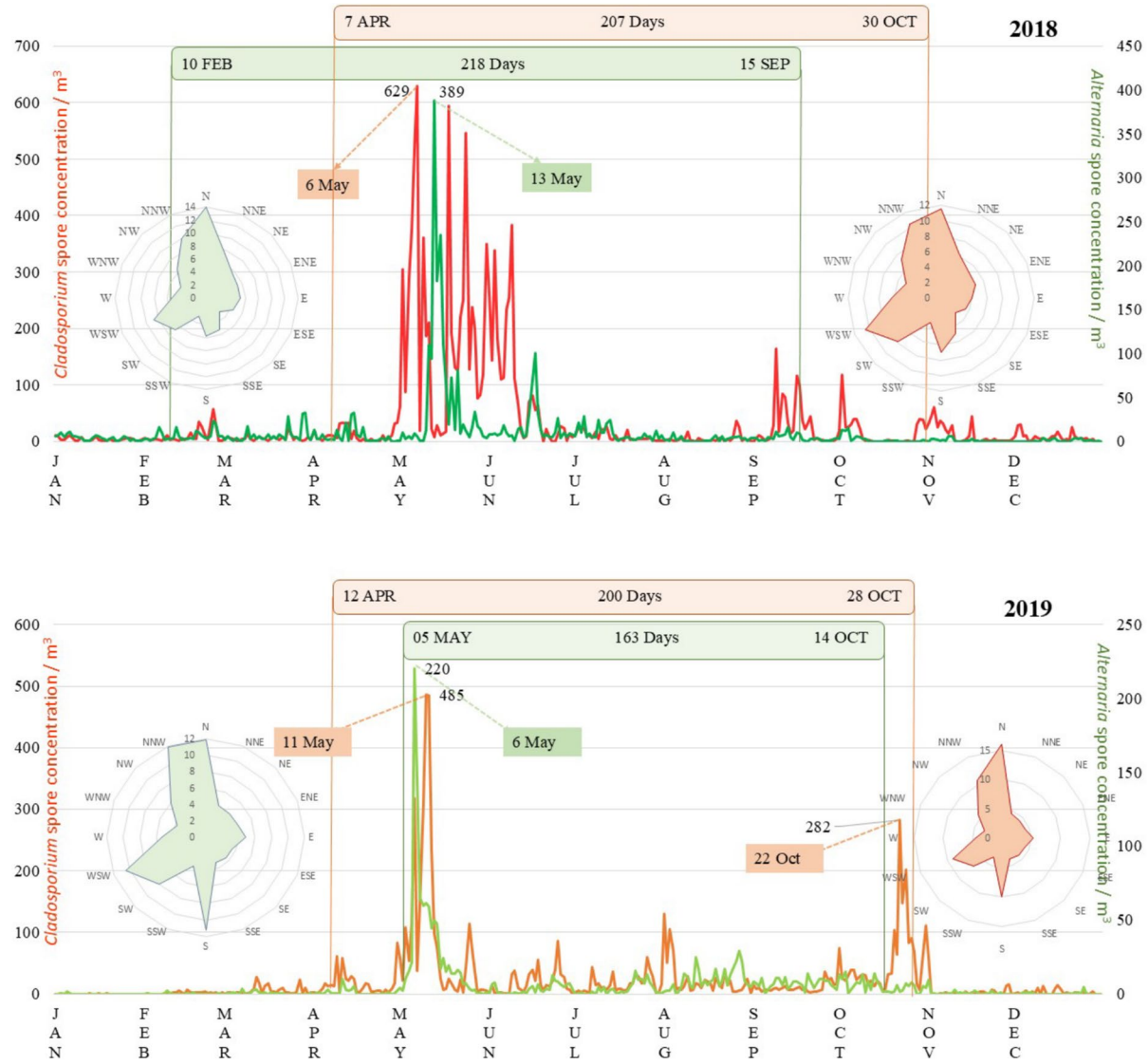


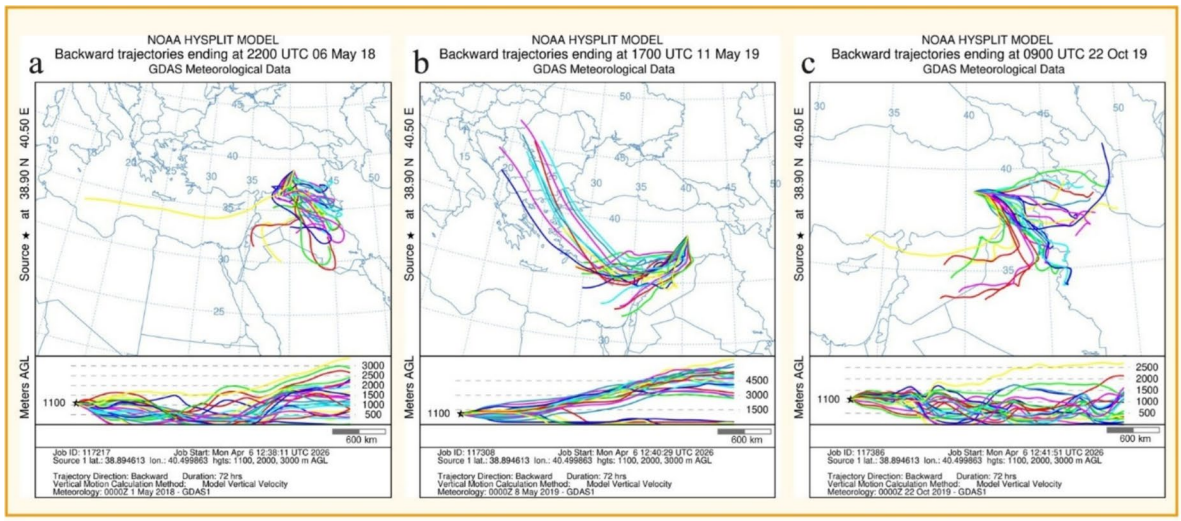
Fig. 4 Daily variations, MSS period durations and start–end–peak dates of *Alternaria* and *Cladosporium* spores and wind directions (%) in the days during MSS periods

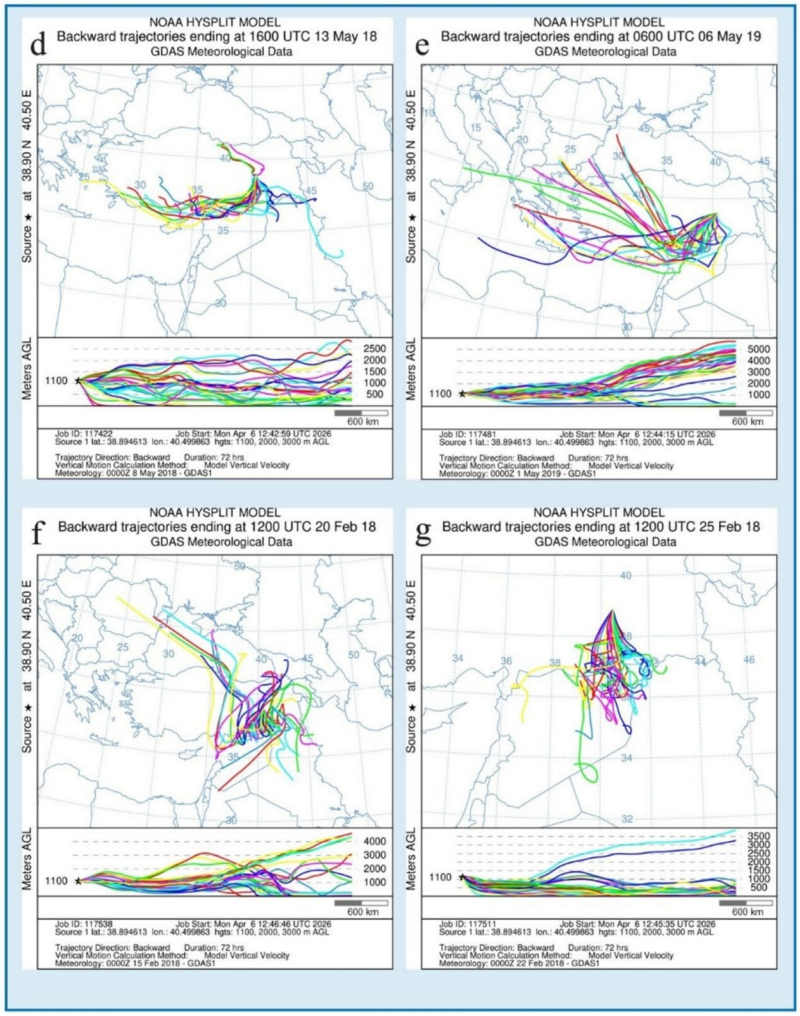
not exceed the threshold on any day during the study (Fig. 4). In contrast, *Alternaria* exhibited marked inter-annual variability; while the MSS began in February during the first year, it was delayed by nearly three months, starting in May during the second year. The *Alternaria* season in 2018 began in February, a period characterized by snow cover, minimal vegetation activity, and low agricultural intensity in the study area. Elevated concentrations were observed over consecutive days, with magnitudes comparable to spring peaks.

3.2 3.2. Long-range transport and backward trajectory analysis

3.2.1 Dominant air mass pathways for spore episodes

Backward trajectory analysis (Fig. 5) indicated that peak spore episodes were associated with distinct air mass pathways that reached Bingöl. For *Cladosporium*, the highest concentration events in both 2018 (Fig. 5a) and 2019 (Fig. 5b-c), including the


a
NOAA HYSPLIT MODEL
Backward trajectories ending at 2200 UTC 06 May 18
GDAS Meteorological Data
b
NOAA HYSPLIT MODEL
Backward trajectories ending at 1700 UTC 11 May 19
GDAS Meteorological Data
c
NOAA HYSPLIT MODEL
Backward trajectories ending at 0900 UTC 22 Oct 19
GDAS Meteorological Data
Source ★ at 38.90 N 40.50 E
Meters AGL
600 km


d
NOAA HYSPLIT MODEL
Backward trajectories ending at 1600 UTC 13 May 18
GDAS Meteorological Data
e
NOAA HYSPLIT MODEL
Backward trajectories ending at 0600 UTC 06 May 19
GDAS Meteorological Data
f
NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 20 Feb 18
GDAS Meteorological Data
g
NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 25 Feb 18
GDAS Meteorological Data
Source ★ at 38.90 N 40.50 E
Meters AGL
600 km

◂**Fig. 5** Air masses' movement in Bingöl city center—*Cladosporium*: **a** peak date 2018, **b** peak date 2019, **c** 2nd peak date 2019; *Alternaria*: **d** peak date 2018, **e** peak date 2019, **f/g** unexpected peaks 2018

autumn peak, were associated with air masses originating from the southern sector, passing over the Mediterranean basin and the Mesopotamian lowlands before reaching the study area. In contrast, *Alternaria* peaks exhibited greater source heterogeneity, being associated with both northern and southern air masses. Trajectories originating from the Black Sea region and passing over Central Anatolia were observed in 2018 (Fig. 5d), while the 2019 peak (Fig. 5e) was predominantly associated with air masses from the southern sector, also passing over the Mesopotamian lowlands before reaching the study area.

During the unexpected *Alternaria* peaks in February, which occurred outside the typical growing season, when local spore production is expected to be minimal where air masses were traced back to the southern regions over the Mesopotamian plains (Fig. 5f-g), indicating a contribution of long-range transport.

3.2.2 Vertical profiles and basin intrusion dynamics

Vertical trajectory profiles (Fig. 5a-g) exhibited substantial variation in altitude for both taxa, showing no uniform altitude pattern. Trajectories were observed at various atmospheric levels, ranging from the near-surface layers (approx. 500 m AGL) to the upper troposphere (up to 5000 m AGL) during their transit. Despite this vertical scattering, a common feature across all peak episodes—including the unexpected February peaks where local production was minimal due to snow cover—was a final descending pattern as trajectories approached the study area, with air masses dropping toward the basin's interior regardless of their initial altitude or fungal taxa.

3.3 3.3. Intra-diurnal patterns and wind niche partitioning

3.3.1 Hourly spore rhythms

When the intra-diurnal variation of *Cladosporium* and *Alternaria* spores was evaluated based on the average values of the two study years, clear temporal patterns emerged (Figs. 6–7). *Cladosporium* concentrations were lowest at night and peaked in the afternoon, coinciding with S winds as indicated by the meteorological wind rose in Fig. 6. *Alternaria* concentrations peaked in the early morning under predominant N winds, demonstrating clear temporal and directional niche partitioning between the two taxa. Minimum concentrations for both species were consistently observed during nighttime hours. Collectively, these intra-diurnal patterns highlight the influence of wind direction on peak spore transport.

3.3.2 Wind direction and speed

During the MSS, northerly winds were dominant (~ 33–37%), followed by southerly flows (~ 17–22%). Despite a shift toward more southerly winds in 2019 (Fig. 4), this change alone was insufficient to drive inter-annual variability in total spore loads. Meteorological conditions during peak days indicated that wind speeds were consistently higher than monthly averages in both years. Peak wind speeds reached 1.0–1.1 m/s for *Cladosporium* and 0.8–0.9 m/s for *Alternaria*, exceeding monthly mean values (0.66–0.72 m/s).

Detailed analysis of wind direction frequencies during peak concentration hours (in MSS) revealed a marked inter-annual shift for *Alternaria*. Northerly component winds (N, NNE, NE, NNW) decreased from approximately 53% in 2018 to 28% in 2019, while southerly components (S, SSE, SE, SSW) increased from about 11% to 27%. In contrast, *Cladosporium* exhibited relatively stable directional distributions during peak hours, with northerly components remaining around 29% and 28%, and southerly components around 32% and 27% in 2018 and 2019, respectively (Fig. 7).

Furthermore, wind direction analysis during the MSS periods revealed that northern winds dominated in 2018, accounting for a substantial proportion of observations, whereas a clear shift toward southern winds was observed in 2019 (Fig. 4). These deviations in wind direction, together with elevated wind speeds, were consistent with the backward trajectory analysis, which showed that air masses during the February episode originated predominantly from southern regions (Fig. 5). These patterns are consistent with the influence of long-range transport,

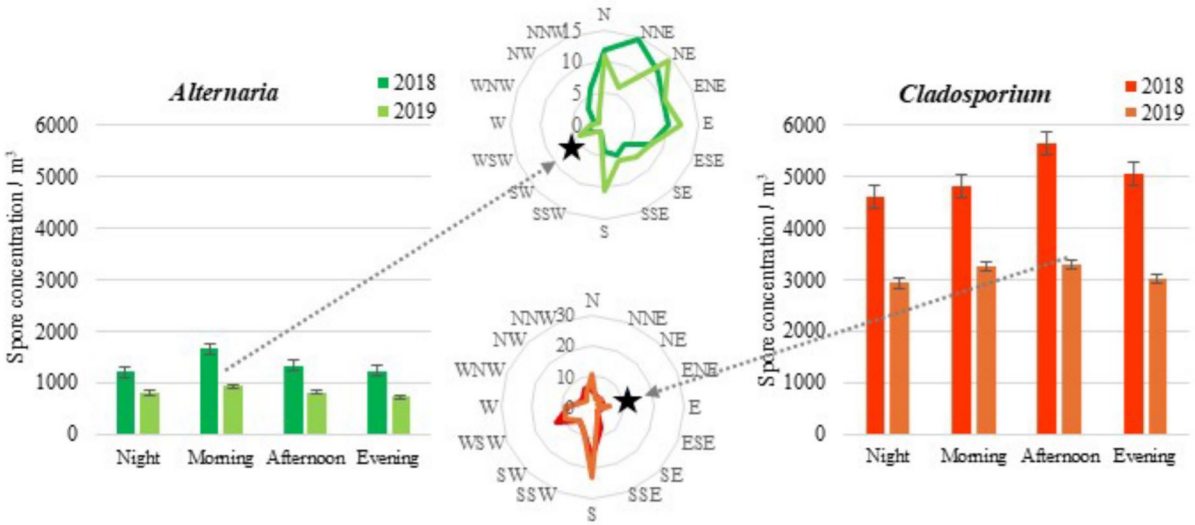


Fig. 6 Intra-diurnal variations in *Cladosporium* and *Alternaria* spores in the Bingöl Atmosphere (average values obtained separately for two years) (night: 12:00 AM–6:00 AM, morning: 6:00 AM–12:00 PM, afternoon: 12:00 PM–6:00 PM, and evening: 6:00 PM–12:00 AM), and prevailing wind directions (%) during the time periods when maximum concentrations were detected in MSS periods (*asterisks indicate statistically significant differences between years*)

potentially associated with synoptic-scale dust intrusion events (Fig. 5); however, in the absence of direct dust measurements, this interpretation should be treated with caution, and local contributions cannot be entirely excluded.

To examine the broader meteorological context and its potential association with the general decline in spore concentrations observed in 2019, despite the absence of significant differences in daily mean meteorological variables, a detailed analysis of wind direction patterns was conducted for the MSS period. The Chi-squared test revealed a highly significant inter-annual variation in the overall hourly wind profiles ($\chi^2 = 204.73$, $p < 0.001$). This pattern was further explored by separately analyzing the morning and afternoon wind dynamics, which represent key periods for spore release and transport. The analysis of the morning period showed a statistically significant difference between the two years ($\chi^2 = 46.759$, $p < 0.001$), and a similar difference was observed in the afternoon period ($\chi^2 = 47.008$, $p < 0.001$). Overall, these results demonstrate that wind direction during the MSS exhibits significant inter-annual variability, with intra-diurnal differences associated with specific wind sectors.

3.4 3.4. Meteorological drivers and lag effects

Correlation analysis showed that *Alternaria* spore concentrations were significantly associated with all evaluated meteorological parameters ($p < 0.05$). Specifically, it showed a significant positive correlation with mean temperature and wind speed, and a significant negative correlation with relative humidity and total precipitation (Fig. 8). Similarly, *Cladosporium* spore concentrations were significantly and positively correlated with temperature and wind speed, and negatively correlated with relative humidity (Fig. 8). However, the negative correlation between *Cladosporium* and total precipitation was not statistically significant ($r = -0.07$, $p > 0.05$). Notably, mean temperature demonstrated the strongest positive correlation for both spore types.

Multiple linear regression analysis indicated that temperature was a significant positive predictor of both *Alternaria* and *Cladosporium* spore concentrations ($p < 0.05$) (Table 1). While relative humidity showed no significant effect on *Alternaria*, it was a significant positive predictor of *Cladosporium* ($p < 0.05$). Notably, this positive effect in the regression model contrasts with the negative relationship

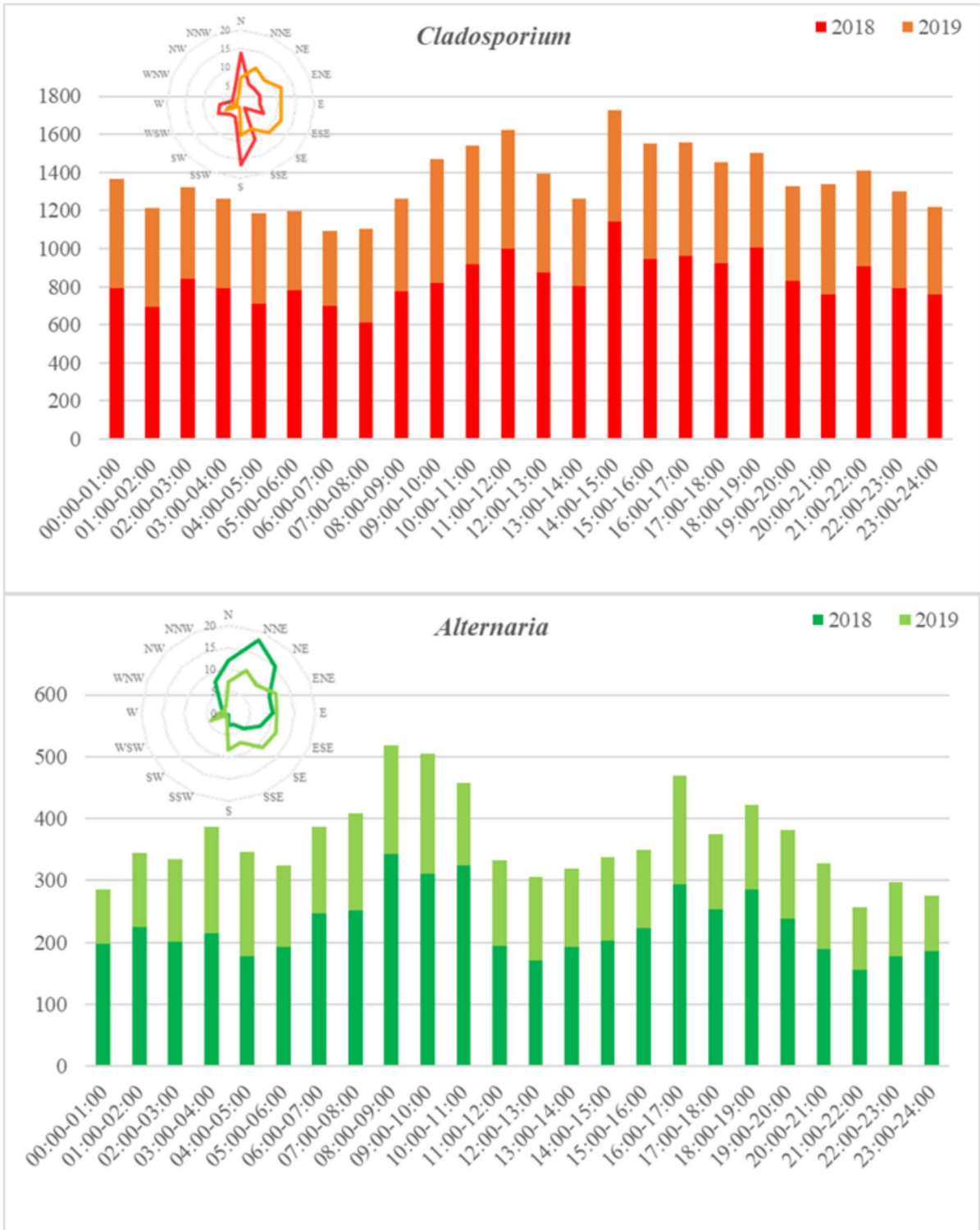


Fig. 7 Intra-diurnal variation in airborne *Alternaria* and *Cladosporium* spores in Bingöl. The wind roses indicate the wind direction (%) during the hours when spore concentrations were highest in the MSS duration

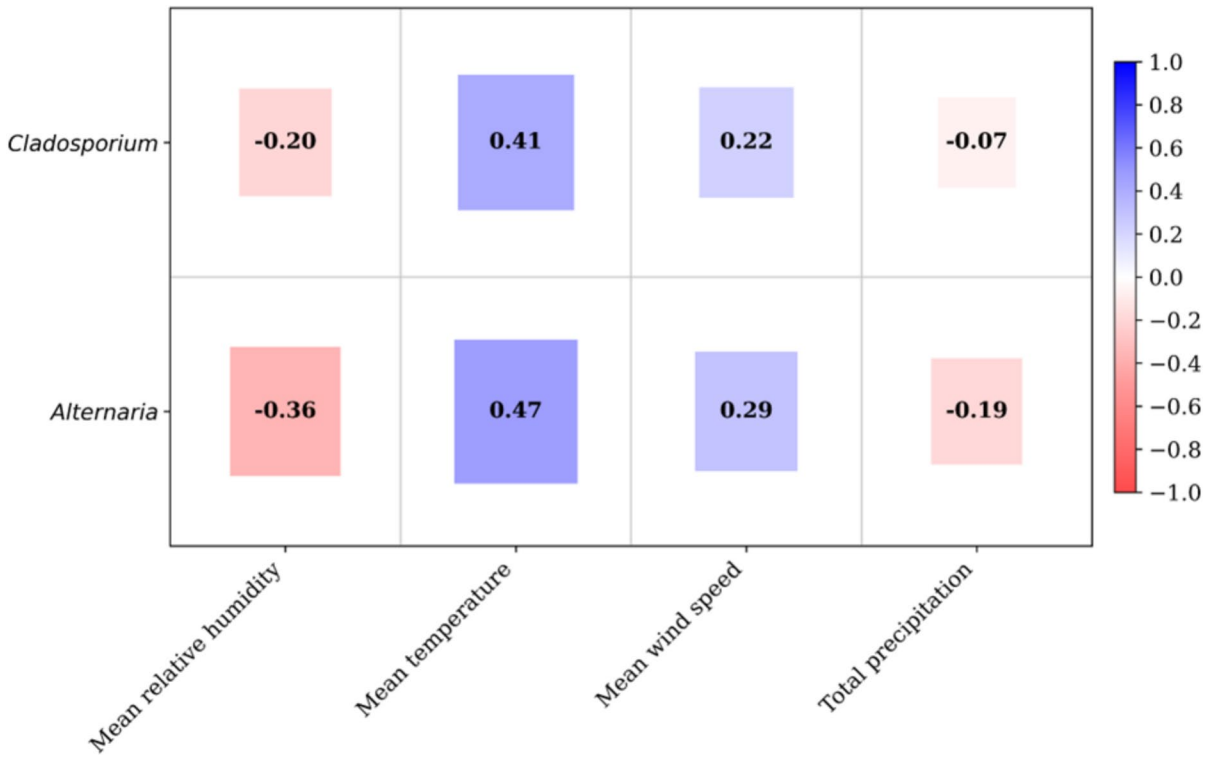


Fig. 8 Spearman's rank correlation heatmap showing relationships between daily atmospheric spore concentrations (*Alternaria* and *Cladosporium*) and meteorological parameters. The color scale represents the correlation coefficient (r_s), with blue indicating positive and red indicating negative correlations

observed in the Spearman analysis. In contrast, wind speed and total precipitation were not identified as significant predictors for either taxon. Among wind directions, east–southeasterly (E–SE) winds were significantly associated with increased spore concentrations for both taxa ($p < 0.05$). Seasonal effects were also evident, with May representing the strongest positive effect on both taxa ($p < 0.01$) (Table 1), confirming the pronounced spring peak observed in the dataset (Fig. 4). Overall, the models explained approximately 40% of the variance in spore concentrations.

Finally, lagged regression analysis demonstrated that precipitation had a delayed positive effect on spore concentrations (Fig. 2). *Cladosporium* responded more rapidly, showing a significant increase one day after precipitation ($p < 0.05$), whereas both taxa exhibited increased concentrations three days after precipitation ($p < 0.05$). These findings indicate short-term delayed responses following precipitation events, whereas no significant effect was observed in the same-day analysis.

4 Discussion

4.1 4.1. Spore seasonality and comparative aerobiological dynamics

Although the concentration of *Alternaria* spores in the atmosphere of Bingöl Province was lower than that of *Cladosporium*, *Alternaria* is considered a more clinically significant allergen due to its higher allergenic potency and lower sensitization threshold (Dixit et al., 2000; Şen & Asan, 2001; Takahashi, 1997). Supporting this clinical focus, compared to European data, where the median number of days above threshold was 42.5 for *Alternaria* and 64 for *Cladosporium* (Ščevková et al., 2026), our study site showed markedly lower seasonal exposure. This highlights that the population in Bingöl is exposed to far fewer days

with clinically relevant spore concentrations—in fact, recorded levels for *Cladosporium* never exceeded the clinical threshold—suggesting that these low exposure levels are primarily associated with local climatic conditions, shorter sporulation periods, and the complex topography that restricts fungal proliferation compared to continental environments.

Indeed, *Alternaria* and *Cladosporium* are the most frequently studied airborne fungal spores, widely recognized for their broad distribution across various climatic regions (Anees-Hill et al., 2022; Gravesen, 1979). Consistent with their ecological roles, like *Cladosporium, Alternaria* species live as saprophytes or parasites on many plants, and these two fungal spore species consistently represent the dominant aeroallergens (Nussbaum, 1991).

In our study, monthly spore concentrations in 2018 were evaluated together with meteorological factors and compared with those from 2019. The observed differences in concentration peaks were associated with variations in sporulation periods and meteorological conditions (Dugan et al., 2004). In January 2019, the average temperature reflected significantly colder winter conditions than in 2018. The comparative temperature drop observed in April 2019 compared to the previous year suggested a delayed and cooler spring in 2019. The faster warming of the air in the spring of 2018 was accompanied by a more rapid increase in fungal spore concentrations compared to 2019 (Fig. 3).

In both years, *Cladosporium* spores exhibited spring and autumn peaks, whereas *Alternaria* spores showed a clear spring peak (Fig. 3). The autumn peak of *Cladosporium* differed between the two years, likely due to variations in temperature and humidity conditions. Overall, the colder winter and hotter, drier summer conditions in 2019 may partly explain the lower spore concentrations compared to 2018. Notably, studies in Greece similarly report *Cladosporium* and *Alternaria* spores as dominant in spring and autumn (Katsimpris et al., 2022; Komnos et al., 2022). These findings, together with our results, clarify the reasons for observed seasonal peaks within this geographic context.

When examining these dynamics from an MSS perspective, *Alternaria* and *Cladosporium* spores were most abundant in May (Fig. 4). Although MSS periods were reported from Salamanca (M-W Spain), peak *Cladosporium* concentrations occurred later, in June–July (Antón et al., 2019). On the Black Sea coast, MSS periods begin earlier than in Europe (Grinn-Gofroń et al., 2020), but later than in Bingöl. Similarly, in nearby Elazığ Province, peak periods occurred later, in June for *Cladosporium* and July for *Alternaria* (Kilic et al., 2020).

4.2 4.2. Effects of meteorology and lagged biological responses

Our results confirmed that *Alternaria* and *Cladosporium* spore concentrations are positively correlated with temperature and solar intensity (Table 1), aligning with established aerobiological research (Angulo-Romero et al., 1999; Corden & Millington, 2001; Giner et al., 2001; Hjelmroos, 1993; Solomon, 1978; Stennett & Beggs, 2004; Troutt & Levetin, 2001). Although changes in humidity and precipitation generally appear less determinant than temperature fluctuations, fungi typically require moisture for growth and sporulation, and many spores are subsequently transported in the atmosphere (Pakpour et al., 2015).

Heavy precipitation can severely reduce spore concentrations through atmospheric washout. In our study, in parallel with previous findings (Aira et al., 2008, 2012; Hollins et al., 2004; Katial et al., 1997; Oliveira et al., 2009), high rainfall and same-day humidity negatively affected atmospheric spore levels (Fig. 8), with a significant negative correlation observed between *Cladosporium* spores and precipitation as reported in Vélez-Pereira et al. (2019).

In contrast to same-day effects, lagged analyses revealed that precipitation had a positive delayed effect on spore concentrations, particularly 1–3 days after precipitation (Fig. 2), suggesting that moisture influences sporulation indirectly through short-term biological processes (Knutsen et al., 2012; Kurkela, 1997). These temporal dynamics align strongly with previous observations; for instance, models from Catalonia similarly demonstrated that accumulated precipitation over the preceding three days significantly increases spore concentrations following initial washout effects (Vélez-Pereira et al., 2019). Furthermore, our observation of a rapid 1-day response for *Cladosporium* is closely supported by cross-correlation analyses in a Finnish forest, which identified a significant biological response approximately 14h post-precipitation (Kurkela, 1997).

In this study, *Cladosporium* spores showed a statistically significant positive correlation with wind speed (Fig. 8). *Cladosporium* and *Alternaria* spores are known to be easily dispersed by wind (Li & Kendrick, 1994); however, previous findings regarding the effect of wind speed are inconsistent. While some studies reported no effect on spore concentrations (Burch & Levetin, 2002; Sabariego et al., 2000), others found a positive relationship (Giner et al., 2001). These differences may be due to variations in sampling areas and the presence of natural and artificial barriers, as well as long-distance transport in these areas.

Finally, the relationship between *Cladosporium* spores and relative humidity highlights the importance of the statistical approach employed. The divergent results between univariate and multivariate models regarding relative humidity suggest that its effect is likely masked by temperature interactions in simpler correlation analyses. This apparent discrepancy likely reflects interactions among predictors in the multivariate model, where the effect of relative humidity is evaluated while controlling for temperature and other variables. *Cladosporium*'s strong positive response to temperature is consistent with previous studies (Almeida et al., 2018; Kasprzyk et al., 2016; Sindt et al., 2016), and the combined effect of warm and moderately humid conditions can explain the observed spore peaks.

4.3 4.3. Topographical modulation of spore distribution and niche partitioning

Vegetation serves as the primary substrate for fungi. Bingöl Province, located in a basin surrounded by high mountains, contains the largest forested area in Eastern Anatolia. Winter conditions likely have little effect on airborne spore dynamics, as many plants are defoliated, leaves may often be covered with snow, and low temperatures limit sporulation. Predictably, *Cladosporium* and *Alternaria* spores increase with the emergence of plants in spring, explaining the high concentrations during this period (Li & Kendrick, 1994).

During the peak summer months, the high average temperatures recorded in both years likely contributed to the decrease in fungal spore concentration, which is often attributed to the inhibitory effects of high temperature, intense solar radiation and low humidity (Aira et al., 2012; Calderón et al., 1997). Fungal spores only develop within a specific temperature range, and concentrations consistently decline under extreme temperatures (Oliveira et al., 2005). In late summer and autumn, spore intensity rises, reaching minima in winter months such as January and February, with *Cladosporium* and *Alternaria* peaking in September (Oliveira et al., 2005).

Local topography-driven wind systems (e.g., anabatic and katabatic flows) may contribute to the redistribution of spores from nearby vegetation within the basin, particularly under conditions where temperature and wind speed are sufficient to trigger local release, as previously suggested by Calderón et al. (1997). However, this mechanism mainly applies to locally sourced spore variability and does not fully account for peak episodes observed in the study.

The literature consistently indicates that spore concentrations in the air exhibit distinct daily variations, often recording peak levels in the afternoon or late evening, while minima typically occur during the night or early morning hours (Aira et al., 2008; Ricci et al., 1995; Rodríguez-Rajo & Iglesias, 2005). In the present study, however, *Alternaria* spores reached their maximum concentrations during the early morning hours in both study years. While some researchers report similar morning peaks, others have observed considerable variation ranging from early morning to late evening (Bardei et al., 2017; Corden & Millington, 2001; Giner et al., 1998; Stach, 1997). This intra-diurnal variability is often attributed to site-specific environmental conditions. For instance, *Alternaria* is known to sporulate during periods of lower solar radiation (Srivastava & Wadhwani, 1992), and its morning increases in the Bingöl atmosphere may be associated with the synchronized rise in temperature and wind speed during these hours (Burch & Levetin, 2002; Jones & Harrison, 2004).

In contrast, *Cladosporium* concentrations in Bingöl were highest in the afternoon, a pattern consistent with several studies reporting elevated levels during midday hours (Bardei et al., 2017; Helander & Pessi, 1991; Li & Kendrick, 1995). Overall, the distinct intra-diurnal cycles observed for both taxa reflect the dynamic influence of changing meteorological conditions throughout the day (Calderón et al., 1997). In addition, the alignment of *Alternaria* morning peaks

with northerly winds and *Cladosporium* afternoon peaks with southerly winds suggests a directional component in intra-diurnal partitioning.

Nevertheless, given that these hours represent only a small fraction of the extended MSS, peak-hour wind patterns alone may not fully account for inter-annual variability in spore concentrations, indicating that favorable wind direction is necessary but not sufficient for elevated peaks. These temporal shifts, particularly the morning–afternoon partitioning between the two species, provide a crucial baseline for evaluating the influence of directional wind sectors and subsequent long-range transport mechanisms.

Building on this premise, the seasonal and intra-diurnal dynamics of *Alternaria* and *Cladosporium* spores in the Bingöl atmosphere are shaped by a complex interaction between local topographical features and regional air mass movements. The temporal and directional niche partitioning observed in the intra-diurnal distribution of spores highlights the decisive role of wind sectors. Indeed, the Chi-squared analysis performed on the overall hourly wind profiles during the MSS period revealed a highly significant inter-annual variation. This meteorological pattern was further contextualized by analyzing critical time windows for spore release; the morning period showed a striking and statistically significant difference between the two years, a trend that clearly extended into the afternoon hours. This statistical framework provides a mechanistic basis for the observed peaks, where *Alternaria* reaches maximum levels during the morning hours under predominant northerly (N) winds, while *Cladosporium* peaks in the afternoon, coinciding with southerly (S) wind components.

4.4 4.4. Long-range transport pathways and the February anomaly of *Alternaria*

To address the limitations of local meteorological interpretation, backward trajectory analysis was used to evaluate regional-scale transport pathways. Results showed that peak spore episodes were frequently associated with air masses originating from the Mesopotamian lowlands and the Mediterranean basin (Fig. 5), highlighting the importance of large-scale atmospheric transport processes beyond local meteorological variability. Inter-annual differences further indicated that variations in dominant air mass origin play a key role in modulating seasonal spore levels, with the second year characterized by more frequent northerly and humid boreal (northeast) flows coinciding with comparatively lower concentrations during peak periods.

East–southeasterly (E–SE) winds were identified as a significant positive predictor of increased concentrations for both taxa (Table 1), supporting the influence of directional air mass inputs. Literature evidence indicates that the role of southeasterly flows varies significantly across regions. While studies in Ireland (O'Connor et al., 2014) and Denmark (Olsen et al., 2020) associate these winds with elevated *Alternaria* and *Cladosporium* concentrations—often linked to agricultural source regions—research from Spain reports a negative relationship, emphasizing strong site-specific controls (Reyes et al., 2009).

Back-trajectory analysis further demonstrated that spores can be transported over long distances, with *Alternaria* previously reported to travel up to several hundred kilometers (Grewling et al., 2022; Levetin, 2016). While HYSPLIT has been widely used for studying such long-range transport, mostly in regions with relatively flat or uncomplicated topography (Grewling et al., 2022; Sadyś et al., 2015; Uguz, 2025), our basin-shaped study area presents a unique case where local terrain likely traps spores and alters air mass pathways. Situated at the northern terminus of Mesopotamia, Bingöl serves as the primary topographical transition where air masses ascend from the Mesopotamian plains toward the Anatolian plateau. Our HYSPLIT analysis confirms that peak concentration episodes are frequently associated with southerly air masses originating from the Mediterranean basin and the Mesopotamian lowlands. This southern corridor—encompassing the Fertile Crescent—is particularly critical, as croplands (where wheat remains the dominant staple) have been consistently identified as primary reservoirs for *Alternaria* and *Cladosporium* spores (Grinn-Gofroń et al., 2020; Olsen et al., 2020), corroborating the likelihood of long-distance atmospheric transport to the study site.

The practical significance of this long-range transport mechanism is most evident during the

unexpected *Alternaria* peaks recorded on February 20 and 25, a period when local vegetation is dormant under snow cover. These unexpected peaks were traced back to low-altitude transport from the southern Mesopotamian plains, suggesting that even during periods of limited local production, regional airflows—notably the seasonal Simoom winds—possess the capacity to transport exogenous spores into the Bingöl atmosphere. While the occurrence of the February peak in only one of the two years suggests an unusual event, longer-term monitoring is required to determine whether such peaks are rare or part of a recurring pattern. Nevertheless, the findings of this study, supported by HYSPLIT-based evidence (Grinn-Gofroń et al., 2016; Sadyś et al., 2015), provide significant insights into the role of long-distance transport in the Eastern Anatolia region.

4.5 4.5. Atmospheric subsidence and basin-scale influx mechanisms

This transport process is likely supported by the dynamic vertical profiles observed in the trajectories. While some air masses reached upper tropospheric levels (up to 5000 m AGL), the characteristic descending pattern observed as they approached the region is particularly noteworthy. In a basin topography like Bingöl's, such downward air movements suggest a degree of atmospheric subsidence. This physical settling of air masses, potentially influenced by the surrounding mountain barriers, may facilitate the deposition of long-range transported spores into the lower atmosphere.

Thus, the local topography might act as a natural catchment area, potentially capturing fungal inocula from higher-altitude flows and contributing to the sudden concentration peaks recorded at ground level. Overall, these dynamics suggest that the airborne spore load in Bingöl is governed by a complex interplay between local sporulation and long-distance transport mechanisms. While advanced trajectory-based methods (e.g., clustering, PSCF, and residence time analysis) were beyond the scope of the present study, they represent valuable approaches for future longitudinal research. Although the present findings provide strong indirect evidence for long-range transport, definitive confirmation of source regions requires more integrated approaches combining trajectory modeling with in situ aerosol monitoring.

5 Conclusions

This study demonstrates that airborne spore dynamics in the Bingöl basin are shaped by the interaction between local topoclimatic conditions and regional air mass transport. Our findings highlight that consistent inter-annual shifts in wind patterns and delayed meteorological responses are the primary drivers of these observed fluctuations. While northerly winds were associated with lower spore concentrations, southerly air masses originating from the Mesopotamian plains were identified as the primary drivers of peak episodes. The trajectory modeling analysis further illustrates how basin morphology acts as a natural geographic trap, where descending air motions facilitate the deposition of spores from distant sources. This mechanism was most clearly evidenced by the anomalous February *Alternaria* peaks, highlighting the decisive role of exogenous influx even during local dormancy. These results suggest that in topographically complex regions, atmospheric spore loads are determined by specialized transport systems that deviate from general regional patterns. Consequently, future research should focus on long-term monitoring within such geographic traps to fully decode the complex synchronization between basin morphology and trans-boundary bioaerosol transport.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request. All key findings and supporting data are included within the article and its supplementary materials.

Declarations

Conflict of interest The authors declare no competing interests.

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References

Adhikari, P., Khatri-Chhetri, G. B., Shrestha, S. M., & Marahatta, S. (2016). Study on prevalence of mycoflora in wheat seeds. *Turkish Journal of Agriculture-Food Science and Technology, 4*(1), 31–35. https://doi.org/10.24925/turjaf.v4i1.31-35.509

Ahmet, C. A. F., Irmak, M. A., & Yılmaz, H. (2016). Bingöl ili yeşil alanlarında kullanılan odunsu bitkiler ve kullanım amaçları. *Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 6*(2), 103–110.

Aira, M. J., Rodríguez-Rajo, F. J., Fernández-González, M., Seijo, C., Elvira-Rendueles, B., Gutiérrez-Bustillo, M., Abreu, I., Pérez-Sánchez, E., Oliviera, M., Recio, M., Morales, J., & Muñoz-Rodríguez, A. F. (2012). *Cladosporium* airborne spore incidence in the environmental quality of the Iberian Peninsula. *Grana, 51*(4), 293–304. https://doi.org/10.1080/00173134.2012.717636

Aira, M. J., Rodríguez-Rajo, F. J., & Jato, V. (2008). 47 annual records of allergenic fungi spore: Predictive models from the NW Iberian Peninsula. *Annals of Agricultural and Environmental Medicine, 15*(1), 91–98.

Akgül, H., Yılmazkaya, D., Akata, I., Tosunoğlu, A., & Bıçakçı, A. (2016). Determination of airborne fungal spores of Gaziantep (SE-Turkey). *Aerobiologia, 32*, 441–452. https://doi.org/10.1007/s10453-015-9417-z

Almeida, E., Caeiro, E., Todo-Bom, A., Ferro, R., Dionísio, A., Duarte, A., & Gazarini, L. (2018). The influence of meteorological parameters on *Alternaria* and *Cladosporium* fungal spore concentrations in Beja (Southern Portugal): Preliminary results. *Aerobiologia, 34*(2), 219–226. https://doi.org/10.1007/s10453-018-9508-8

Anees-Hill, S., Douglas, P., Pashley, C. H., Hansell, A., & Marczylo, E. L. (2022). A systematic review of outdoor airborne fungal spore seasonality across Europe and the implications for health. *Science of the Total Environment, 818*, Article 151716. https://doi.org/10.1016/j.scitotenv.2021.151716

Angulo-Romero, J., Mediavilla-Molina, A., & Domínguez-Vilches, E. (1999). Conidia of *Alternaria* in the atmosphere of the city of Cordoba, Spain in relation to meteorological parameters. *International Journal of Biometeorology, 43*(1), 45–49. https://doi.org/10.1007/s004840050115

Antón, S. F., de la Cruz, D. R., Sánchez, J. S., & Sánchez Reyes, E. (2019). Analysis of the airborne fungal spores present in the atmosphere of Salamanca (MW Spain): A preliminary survey. *Aerobiologia, 35*(3), 447–462. https://doi.org/10.1007/s10453-019-09569-z

Bardei, F., Bouziane, H., Trigo, M. D. M., Ajouray, N., El Haskouri, F., & Kadiri, M. (2017). Atmospheric concentrations and intradiurnal pattern of *Alternaria* and *Cladosporium* conidia in Tétouan (NW of Morocco). *Aerobiologia, 33*(2), 221–228. https://doi.org/10.1007/s10453-016-9465-z

Bednarz, A., & Pawlowska, S. (2016). A fungal spore calendar for the atmosphere of Szczecin, Poland. *Acta Agrobotanica*, *69*(3).

Bouziane, H., Latge, J. P., Fitting, C., Mecheri, S., Lelong, M., & David, B. (2005). Comparison of the allergenic potency of spores and mycelium of *Cladosporium*. *Allergologia Et Immunopathologia, 33*(3), 125–130. https://doi.org/10.1157/13075694

Burch, M., & Levetin, E. (2002). Effects of meteorological conditions on spore plumes. *International Journal of Biometeorology, 46*(3), 107–117. https://doi.org/10.1007/s00484-002-0127-1

Calderón, C., Lacey, J., McCartney, A., & Rosas, I. (1997). Influence of urban climate upon distribution of airborne *Deuteromycete* spore concentrations in Mexico City. *International Journal of Biometeorology, 40*(2), 71–80. https://doi.org/10.1007/s004840050021

Corden, J. M., & Millington, W. M. (2001). The long-term trends and seasonal variation of the aeroallergen *Alternaria* in Derby, UK. *Aerobiologia, 17*(2), 127–136. https://doi.org/10.1023/A:1010876917512

D'Amato, G., Chatzigeorgiou, G., Corsico, R., Gioulekas, D., Jäger, L., Jäger, S., Konou-Fili, K., Kouridakis, S., Liccardi, G., Meriggi, A., Palma-Carlos, A., Palma-Carlos, M. L., Pagan Aleman, A., Parmiani, S., Puccinelli, P., Russo, M., Spieksma, F. T. M., Torricelli, B., & Wuthrich, B. (2007). Evaluation of the prevalence of skin prick test positivity to *Alternaria* and *Cladosporium* in patients with suspected respiratory allergy: A European multicenter study promoted by the subcommittee on aerobiology and environmental aspects of inhalant allergens of the European academy of allergology and clinical immunology. *Allergy, 52*(7), 711–716. https://doi.org/10.1111/j.1398-9995.1997.tb01227.x

Dixit, A., Lewis, W., Baty, J., Crozier, W., & Wedner, J. (2000). Deuteromycete aerobiology and skin-reactivity patterns–A two year concurrent study in Corpus Christi, Texas,

USA. *Grana, 39*(4), 209–218. https://doi.org/10.1080/00173130051084368

Dugan, F. M., Schubert, K., & Braun, U. (2004). Check-list of *Cladosporium* names. *Schlechtendalia, 11*, 1–103.

European Committee for Standardization. Technical Specification CEN/TS 16868: (2015). Ambient air. Sampling and analysis of airborne pollen grains and fungal spores for allergy networks. Volumetric Hirst method. Available from: http://shop.bsigroup.com/ProductDetail/?pid=000000000030314080

Fang, Z., Zhang, J., Guo, W., & Lou, X. (2019). Assemblages of culturable airborne fungi in a typical urban, tourism-driven center of southeast China. *Aerosol and Air Quality Research, 19*(4), 820–831. https://doi.org/10.4209/aaqr.2018.02.0042

Fernández-Rodríguez, S., Sadyś, M., Smith, M., Tormo-Molina, R., Skjøth, C. A., Maya-Manzano, J. M., Silva-Palacios, I., & Gonzalo-Garijo, Á. (2015). Potential sources of airborne *Alternaria* spp. spores in South-west Spain. *Science of the Total Environment, 533*, 165–176. https://doi.org/10.1016/j.scitotenv.2015.06.031

Filali Ben Sidel, F., Bouziane, H., del Mar Trigo, M., El Haskouri, F., Bardei, F., Redouane, A., Kadiri, M., Riadi, H., & Kazzaz, M. (2015). Airborne fungal spores of *Alternaria*, meteorological parameters and predicting variables. *International Journal of Biometeorology, 59*(3), 339–346. https://doi.org/10.1007/s00484-014-0845-1

Galán, C., Cariñanos González, P., Alcázar Teno, P., & Domínguez Vilches, E. (2007). *Spanish Aerobiology Network (REA): Management and quality manual*. Servicio de Publicaciones de la Universidad de Córdoba.

Galán, C., Smith, M., Thibaudon, M., Frenguelli, G., Oteros, J., Gehrig, R., Berger, U., Clot, B., Brandao, R., EAS QC Working Group. (2014). Pollen monitoring: Minimum requirements and reproducibility of analysis. *Aerobiologia, 30*, 385–395. https://doi.org/10.1007/s10453-014-9335-5

Giner, M. M., Carrión García, J., & Navarro Camacho, C. (2001). Airborne *Alternaria* spores in SE Spain (1993-98). *Grana*. https://doi.org/10.1080/00173130152625842

Giner, M. M., García, J. C., & Sellés, J. G. (1998). Incidence of *Alternaria* spores in the atmosphere of Murcia (SE Spain). Seasonal, monthly and intradiurnal variations. *Journal of Investigational Allergology and Clinical Immunology, 8*, 304–308.

Gioulekas, D., Damialis, A., Papakosta, D., Spieksma, F., Giouleka, P., & Patakas, D. (2004). Allergenic fungi spore records (15 years) and sensitization in patients with respiratory allergy in Thessaloniki-Greece. *Journal of Investigational Allergology and Clinical Immunology, 14*, 225–231. https://doi.org/10.1046/j.1398-9995.2003.00312.x

Górzyńska, A., Grzech, A., Mierzwiak, P., Ussowicz, M., Biernat, M., & Nawrot, U. (2023). Quantitative and qualitative airborne mycobiota surveillance in high-risk hospital environment. *Microorganisms, 11*(4), Article 1031. https://doi.org/10.3390/microorganisms11041031

Gravesen, S. (1979). Fungi as a cause of allergenic disease. *Allergy, 34*, 135–154. https://doi.org/10.1111/j.1398-9995.1979.tb01562.x

Grewling, Ł, Magyar, D., Chłopek, K., Grinn-Gofroń, A., Gwiazdowska, J., Siddiquee, A., Ianovici, N., Kaspryzk, I., Wójcik, M., Lafférsová, J., Majkowska-Wojciechowska, B., Myszkowska, D., Rodinkova, V., Bortnyk, M., alkiewicz, M., Piotrowska-Weryszko, K., Sulborska-Różycka, A., Rybniček, O., Ščevková, J., … Bogawski, P. (2022). Bioaerosols on the atmospheric super highway: An example of long distance transport of *Alternaria* spores from the Pannonian Plain to Poland. *Science of the Total Environment, 819*, Article 153148. https://doi.org/10.1016/j.scitotenv.2022.153148

Grinn-Gofroń, A., Bosiacka, B., Bednarz, A., et al. (2018). A comparative study of hourly and daily relationships between selected meteorological parameters and airborne fungal spore composition. *Aerobiologia, 34*, 45–54. https://doi.org/10.1007/s10453-017-9493-3

Grinn-Gofroń, A., Çeter, T., Pinar, N. M., Bosiacka, B., Çeter, S., Keçeli, T., Myśliwy, M., Acar Şahin, A., & Bogawski, P. (2020). Airborne fungal spore load and season timing in the Central and Eastern Black Sea region of Turkey explained by climate conditions and land use. *Agricultural and Forest Meteorology, 295*, Article 108191. https://doi.org/10.1016/j.agrformet.2020.108191

Grinn-Gofroń, A., Sadyś, M., Kaczmarek, J., Bednarz, A., Pawłowska, S., & Jedryczka, M. (2016). Back-trajectory modelling and DNA-based species-specific detection methods allow tracking of fungal spore transport in air masses. *Science of the Total Environment, 571*, 658–669. https://doi.org/10.1016/j.scitotenv.2016.07.034

Grinn-Gofroń, A., & Strzelczak, A. (2008). Artificial neural network models of relationships between *Alternaria* spores and meteorological factors in Szczecin (Poland). *International Journal of Biometeorology, 52*(8), 859–868. https://doi.org/10.1007/s00484-008-0182-3

Grinn-Gofroń, A., & Strzelczak, A. (2009). Hourly predictive artificial neural network and multivariate regression tree models of *Alternaria* and *Cladosporium* spore concentrations in Szczecin (Poland). *International Journal of Biometeorology, 53*(6), 555–562. https://doi.org/10.1007/s00484-009-0243-2

Haas, D., Ilieva, M., Fritz, T., Galler, H., Habib, J., Kriso, A., Kropsch, M., Ofner-Kopeinig, P., Reinthaler, F. F., Strasser, A., Zentner, E., & Schalli, M. (2023). Background concentrations of airborne, culturable fungi and dust particles in urban, rural and mountain regions. *Science of the Total Environment, 892*, Article 164700. https://doi.org/10.1016/j.scitotenv.2023.164700

Helander, M. L., & Pessi, A. M. (1991). Circadian periodicity of airborne pollen and spores; significance of sampling height. *Aerobiologia, 7*(2), 129–135. https://doi.org/10.1007/BF02270681

Hjelmroos, M. (1993). Relationship between airborne fungal spore presence and weather variables: *Cladosporium* and *Alternaria*. *Grana, 32*(1), 40–47. https://doi.org/10.1080/00173139309436418

Hollins, P. D., Kettlewell, P. S., Atkinson, M. D., Stephenson, D. B., D'amato, J. M., Millington, W. M., & Mullins, J. (2004). Relationships between airborne fungal spore concentration of *Cladosporium* and the summer climate at two sites in Britain. *International Journal of Biometeorology, 48*(3), 137–141. https://doi.org/10.1007/s00484-003-0188-9

Jones, A. M., & Harrison, R. M. (2004). The effects of meteorological factors on atmospheric bioaerosol concentrations—A review. *Science of the Total Environment, 326*(1–3), 151–180. https://doi.org/10.1016/j.scitotenv.2003.11.021

Kallawicha, K., Chen, Y. C., Chao, H. J., Shen, W. C., Chen, B. Y., Chuang, Y. C., & Guo, Y. L. (2017). Ambient fungal spore concentration in a subtropical metropolis: Temporal distributions and meteorological determinants. *Aerosol and Air Quality Research, 17*(8), 2051–2063. https://doi.org/10.4209/aaqr.2016.10.0450

Kasprzyk, I., Rzepowska, B., & Wasylów, M. (2004). Fungal spores in the atmosphere of Rzeszow [South-East Poland]. *Annals of Agricultural and Environmental Medicine*, *11*(2).

Kasprzyk, I., Kaszewski, B. M., Weryszko-Chmielewska, E., Nowak, M., Sulborska, A., Kaczmarek, J., Szymanska, A., Haratym, W., & Jedryczka, M. (2016). Warm and dry weather accelerates and elongates *Cladosporium* spore seasons in Poland. *Aerobiologia, 32*(1), 109–126. https://doi.org/10.1007/s10453-016-9425-7

Katial, R. K., Zhang, Y., Jones, R. H., & Dyer, P. D. (1997). Atmospheric mold spore counts in relation to meteorological parameters. *International Journal of Biometeorology, 41*(1), 17–22. https://doi.org/10.1007/s004840050048

Katsimpris, P., Nikolaidis, C., Deftereou, T.-E., Balatsouras, D., Printza, A., Iliou, T., Alexiadis, T., Chatzisouleiman, I., Samara, M., Constantinidis, J., Lambropoulou, M., & Katotomichelakis, M. (2022). Three-year pollen and fungi calendar in a Mediterranean region of the Northeast Greece. *Allergologia Et Immunopathologia, 50*(2), 65–74. https://doi.org/10.15586/aei.v50i2.491

Kilic, M., Altunoglu, M. K., Akdogan, G. E., Akpınar, S., Taskın, E., & Erkal, A. H. (2020). Airborne fungal spore relationships with meteorological parameters and skin prick test results in Elazig, Turkey. *Journal of Environmental Health Science and Engineering, 18*(2), 1271–1280. https://doi.org/10.1007/s40201-020-00545-1

Knutsen, A. P., Bush, R. K., Demain, J. G., Denning, D. W., Dixit, A., Fairs, A., Greenberger, P. A., Kariuki, B., Kita, H., Kurup, P., Moss, R. B., Niven, R. M., Pashley, C. H., Slavin, R. G., Vijay, H. M., & Wardlaw, A. J. (2012). Fungi and allergic lower respiratory tract diseases. *Journal of Allergy and Clinical Immunology, 129*(2), 280–291. https://doi.org/10.1016/j.jaci.2011.12.970

Komnos, I. D., Michali, M. C., Ziavra, N. V., Katotomichelakis, M. A., & Kastanioudakis, I. G. (2022). A study of airborne pollen grains and fungal spores in the region of Epirus (Northwestern Greece). *Cureus, 14*(6), Article e26335. https://doi.org/10.7759/cureus.26335

Kurkela, T. (1997). The number of *Cladosporium* conidia in the air in different weather conditions. *Grana, 36*(1), 54–61. https://doi.org/10.1080/00173139709362591

Air Resources Laboratory.(2025) HYSPLIT—Hybrid Single-Particle Lagrangian Integrated Trajectory. https://www.ready.noaa.gov/HYSPLIT_traj.php

Levetin, E. (2016). Aerobiology of agricultural pathogens. *Manual of Environmental Microbiology*. https://doi.org/10.1128/9781555818821.ch3.2.8

Li, D. W., & Kendrick, B. (1994). Functional relationships between airborne fungal spores and enviromental factors in Kitchener-Waterloo, Ontario, as detected by canonical correspondence analysis. *Grana, 33*(3), 166–176. https://doi.org/10.1080/00173139409428995

Li, D. W., & Kendrick, B. (1995). A year-round study on functional relationships of airborne fungi with meteorological factors. *International Journal of Biometeorology, 39*(2), 74–80. https://doi.org/10.1007/BF01212584

Liu, H. F., Liao, J., Chen, X. Y., Liu, Q. K., Yu, Z. H., & Deng, J. X. (2019). A novel species and a new record of *Alternaria* isolated from two Solanaceae plants in China. *Mycological Progress, 18*(8), 1005–1012. https://doi.org/10.1007/s11557-019-01504-3

Mansuroğlu, S., & Dağ, V. (2016). Bingöl İlinin peyzaj potansiyelinin kırsal turizm olanakları (SWOT analizi yöntemi kullanılarak) açısından değerlendirilmesi. *Mediterranean Agricultural Sciences, 29*(1), 9–16.

Nilsson, S., & Persson, S. (1981). Tree pollen spectra in the Stockholm region (Sweden). 1973–1980. *Grana, 20*, 179–182. https://doi.org/10.1080/00173138109427661

Nussbaum, M. C. (1991). The literary imagination in public life. *New Literary History, 22*(4), 877–910. https://doi.org/10.2307/469070

O'Connor, D. J., Sadyś, M., Skjøth, C. A., Healy, D. A., Kennedy, R., & Sodeau, J. R. (2014). Atmospheric concentrations of Alternaria, Cladosporium, Ganoderma and Didymella spores monitored in Cork (Ireland) and Worcester (England) during the summer of 2010. *Aerobiologia*, *30*(4), 397–411. https://doi.org/10.1007/s10453-014-9337-3

Ogórek, R., Lejman, A., Pusz, W., Miłuch, A., & Miodyńska, P. (2012). Characteristics and taxonomy of *Cladosporium* fungi. *Mikologia Lekarska, 19*(2), 80–85.

Oliveira, M., Ribeiro, H., & Abreu, I. (2005). Annual variation of fungal spores in atmosphere of Porto: 2003. *Annals of Agricultural and Environmental Medicine, 12*, 309–315.

Oliveira, M., Ribeiro, H., Delgado, J. L., & Abreu, I. (2009). The effects of meteorological factors on airborne fungal spore concentration in two areas differing in urbanisation level. *International Journal of Biometeorology, 53*(1), 61–73. https://doi.org/10.1007/s00484-008-0191-2

Olsen, Y., Skjøth, C. A., Hertel, O., Rasmussen, K., Sigsgaard, T., & Gosewinkel, U. (2020). Airborne *Cladosporium* and *Alternaria* spore concentrations through 26 years in Copenhagen, Denmark. *Aerobiologia, 36*(2), 141–157. https://doi.org/10.1007/s10453-019-09618-7

Özbay, N., Ergun, M., Osmanoğlu, A., & Çakır, A. (2015). Bingöl'de bitkisel üretimin durumu, sorunları ve çözüm önerileri. *Türk Doğa Ve Fen Dergisi, 4*(1), 54–58.

Pakpour, S., Li, D. W., & Klironomos, J. (2015). Relationships of fungal spore concentrations in the air and meteorological factors. *Fungal Ecology, 13*, 130–134. https://doi.org/10.1016/j.funeco.2014.09.008

R Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.

Reyes, E. S., de la Cruz, D. R., Merino, E. S., & Sánchez, J. S. (2009). Meteorological and agricultural effects on airborne *Alternaria* and *Cladosporium* spores and clinical

aspects in Valladolid (Spain). *Annals of Agricultural and Environmental Medicine, 16*(1), 53–61.

Reyes, E. S., de la Cruz, D. R., & Sánchez, J. S. (2016). First fungal spore calendar of the middle-west of the Iberian Peninsula. *Aerobiologia, 32*(3), 529–539. https://doi.org/10.1007/s10453-016-9430-x

Ricci, S., Bruni, M., Meriggi, A., & Corsico, R. (1995). Aerobiological monitoring of *Alternaria* fungal spores: A comparison between surveys in 1992 and 1993 and local meteorological conditions. *Aerobiologia, 11*(3), 195–199. https://doi.org/10.1007/BF02450039

Rodríguez-Rajo, F. J., & Iglesias, I. (2005). Variation assessment of airborne *Alternaria* and *Cladosporium* spores at different bioclimatical conditions. *Mycological Research, 109*(4), 497–507. https://doi.org/10.1017/S0953756204001777

Sabariego, S., Diaz De la Guardia, C., & Alba, F. (2000). The effect of meteorological factors on the daily variation of airborne fungal spores in Granada (southern Spain). *International Journal of Biometeorology, 44*(1), 1–5. https://doi.org/10.1007/s004840050131

Sadyś, M., Kennedy, R., & Skjøth, C. A. (2015). An analysis of local wind and air mass directions and their impact on *Cladosporium* distribution using HYSPLIT and circular statistics. *Fungal Ecology, 18*, 56–66. https://doi.org/10.1016/j.funeco.2015.09.006

Ščevková, J., Dušička, J., Lafférsová, J., Rybníček, O., Štefániková, N., Žilka, M., Zahradníková, E., Hrabovský, M., & Kováč, J. (2026). Predictive modelling of threshold exceedance and airborne concentrations of *Alternaria* and *Epicoccum* spores across bioclimatic regions in Central Europe. *International Journal of Biometeorology, 70*(1), 18. https://doi.org/10.1007/s00484-025-03084-2

Ščevková, J., & Kováč, J. (2019). First fungal spore calendar for the atmosphere of Bratislava, Slovakia. *Aerobiologia, 35*, 343–356. https://doi.org/10.1007/s10453-019-09564-4

Şen, B., & Asan, A. (2001). Airborne fungi in vegetable growing areas of Edirne, Turkey. *Aerobiologia, 17*(1), 69–75. https://doi.org/10.1023/A:1007604417192

Sevindik, M., & Tosunoglu, A. (2025). Temporal variability of aeromycoflora and their relationship with meteorological factors in Şanlıurfa (Türkiye). *Grana, 64*(4), 205–220. https://doi.org/10.1080/00173134.2025.2565187

Sindt, C., Besancenot, J. P., & Thibaudon, M. (2016). Airborne *Cladosporium* fungal spores and climate change in France. *Aerobiologia, 32*(1), 53–68. https://doi.org/10.1007/s10453-016-9422-x

Skjøth, C. A., Damialis, A., Belmonte, J., De Linares, C., Fernández-Rodríguez, S., Grinn-Gofroń, A., Jędryczka, M., Kasprzyk, I., Magyar, D., Myszkowska, D., Oliver, G., Páldy, A., Pashley, C. H., Rasmussen, K., Satchwell, J., Thibaudon, M., Tormo-Molina, R., Vokou, D., Ziemianin, M., & Werner, M. (2016). *Alternaria* spores in the air across Europe: Abundance, seasonality and relationships with climate, meteorology and local environment. *Aerobiologia, 32*(1), 3–22. https://doi.org/10.1007/s10453-016-9426-6

Solomon, W. R. (1978). Aerobiology and inhalant allergens. 1. Pollens and fungi. In E. Middleton, C. E. Reed, & E. F. Ellis (Eds.), *Allergy: Principles and practice* (pp. 312–372). Mosby.

Srivastava, A. K., & Wadhvvani, K. (1992). Dispersion and allergenic manifestations of *Alternaria* airspora. *Grana, 31*(1), 61–66. https://doi.org/10.1080/00173139209427827

Stach, A. (1997). Dobowe wahania stężenia pyłku wybranych taksonów alergogennych w powietrzu nad Poznaniem w 1996 roku. In *Ogólnopolska Konferencja Naukowa*: Biologia kwitnienia, nektarowania i zapylania roslin (pp. 197–203). Lubelskie Towarzystwo Naukowe.

Stein, A. F., Draxler, R. R., Rolph, G. D., Stunder, B. J. B., Cohen, M. D., & Ngan, F. (2015). NOAA'S HYSPLIT atmospheric transport and dispersion modeling system. *Bulletin of American Meteorological Society, 96*(12), 2059–2078. https://doi.org/10.1175/BAMS-D-14-00110.1

Stennett, P. J., & Beggs, P. J. (2004). *Alternaria* spores in the atmosphere of Sydney, Australia, and relationships with meteorological factors. *International Journal of Biometeorology, 49*(2), 98–105. https://doi.org/10.1007/s00484-004-0217-3

Takahashi, T. (1997). Airborne fungal colony-forming units in outdoor and indoor environments in Yokohama, Japan. *Mycopathologia, 139*, 23–33.

Tosunoglu, A., & Bicakci, A. (2015). Seasonal and intradiurnal variation of airborne pollen concentrations in Bodrum, SW Turkey. *Environmental Monitoring and Assessment, 187*(4), Article 167. https://doi.org/10.1007/s10661-015-4384-y

Troutt, C., & Levetin, E. J. I. J. (2001). Correlation of spring spore concentrations and meteorological conditions in Tulsa, Oklahoma. *International Journal of Biometeorology, 45*(2), 64–74. https://doi.org/10.1007/s004840100087

Uguz, U. (2025). Temporal variations in airborne *Alternaria* and *Cladosporium* spores and the effect of meteorological factors: Three years study from a metropolis on the West Anatolian coast. *Aerobiologia, 41*(4), 743–757. https://doi.org/10.1007/s10453-025-09876-8

Vélez-Pereira, A. M., De Linares, C., Canela, M. A., & Belmonte, J. (2019). Logistic regression models for predicting daily airborne *Alternaria* and *Cladosporium* concentration levels in Catalonia (NE Spain). *International Journal of Biometeorology, 63*(12), 1541–1553. https://doi.org/10.1007/s00484-019-01767-1

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