



Identifying patterns of airborne pollen distribution using a synoptic climatology approach

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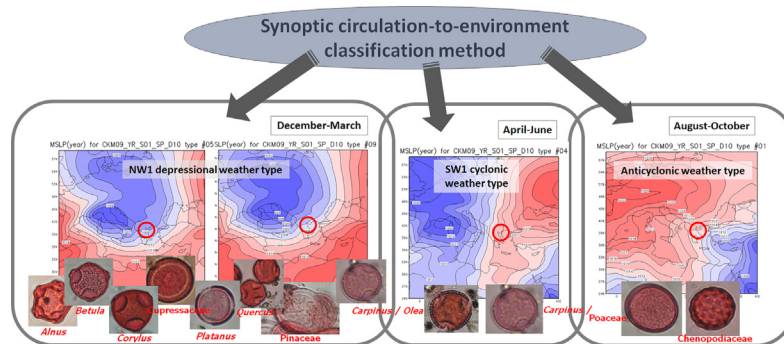
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HIGHLIGHTS

- A circulation-to-environment method was applied to the most abundant pollen types.
- Depressions are linked to high *Carpinus*, *Corylus*, Cupressaceae and *Platanus* pollen.
- The SW1 cyclonic type is linked to high pollen from Oleaceae and Urticaceae.
- Anticyclonic weather is associated with high pollen from Poaceae and Chenopodiaceae.
- Allergenic pollen risk alerts can be enhanced by synoptic climatology models.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 4 November 2019

Received in revised form 4 January 2020

Accepted 8 January 2020

Available online 17 January 2020

Editor: Damia Barcelo

Keywords:

Allergenic pollen
Environmental health
Forecast
Pollen exposure
Synoptic climatology

ABSTRACT

Understanding the mechanisms of pollen release and dispersion in the atmosphere is of high importance, not only for getting an insight on the patterns of movement of these biological particles that are necessary for plants' reproduction, but also because exposure to airborne pollen is a major concern for respiratory allergies worldwide. In this work, a synoptic circulation-to-environment classification method was adopted to elucidate the relationship between distinct atmospheric patterns and pollen levels for the 11 most abundant but also allergenic taxa in Thessaloniki, Greece, for the 15-year period 1987–2001. It was found that the NW1 depressional weather type is associated with the “low winter pollen season” and high levels of pollen from *Carpinus* spp., *Corylus* spp., Cupressaceae, *Platanus* spp., Pinaceae, *Quercus* spp. and Urticaceae. In contrast, the SW1 cyclonic type is linked to the “high spring-summer pollen season” and high levels of pollen from Oleaceae and Urticaceae. On the other hand, anticyclonic weather is associated with the “summer-autumn pollen season” and high levels of Poaceae and Chenopodiaceae pollen in the atmosphere. Regional transport of *Alnus* pollen is linked to a strong high-pressure system centered over Italy, giving light NE winds over northern Greece. These findings shed light to the synoptic climatology of airborne pollen in Thessaloniki and could feed early-warning systems for alerting vulnerable groups of the allergic population.

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1. Introduction

Pollen is the output of plants for their reproduction, which, in anemophilous species, is transported by means of wind. Moreover, airborne pollen is well-known to be implicated in allergic diseases, including bronchial asthma (DellaValle et al., 2012; Erbas et al., 2012), allergic rhinitis (Breton et al., 2006; Greiner et al., 2011) and atopic eczema (Eyerich et al., 2008; Werfel et al., 2015). In the industrialized countries of central and northern Europe pollen is known to adversely affect the population, with the impact being significantly higher among children and adolescents. The severity of allergy to different pollen species varies with climatic factors and latitude, amongst other factors (Damialis et al., 2019b). Additionally, the severity of allergy is known to increase when coupled with high levels of inorganic pollutants (Pérez-Badía et al., 2011). For instance, ozone plays an important role in pollen allergenicity, as it affects both the upper and the lower respiratory system and increases the susceptibility of population to pollen allergens (D'Amato et al., 2007).

Allergies to pollen are expected to change in pattern and/or increase due to earlier flowering of plants, changes in pollen production or invasion of new allergenic plants (Frei and Gassner, 2008) under a changing climate. It is noteworthy that greenhouse gases and especially CO₂ enhance plant growth and consequently pollen production (D'Amato et al., 2007; Albertine et al., 2014). Temperature affects pollen amounts and start and duration of the pollen season in a complex way depending on plant species, period of the year and region (D'Amato and Cecchi, 2008; Weber, 2003); higher temperatures related to climate change are expected to result in earlier flowering. Increased temperature has already been correlated to early flowering and increased pollen concentrations of grass in Southern Spain and wall pellitory in Greece (Frenguelli et al., 2014). Additionally, changes in precipitation regimes are expected to have an impact on pollen concentrations, as precipitation is known to have a double role: during the pollen season, rainfall washes out the atmosphere and has a negative correlation with pollen concentration, whereas, before it, precipitation enhances plant growth and, as a consequence, pollen production (Ribeiro et al., 2003; Weber, 2003; Tormo-Molina et al., 2010).

Although it is widely believed that airborne pollen mainly originates from local sources, such as natural vegetation, ornamental plants and crops (e.g. Adams-Groom et al., 2002; Cariñanos and Casares-Porcel, 2011; Charalampopoulos et al., 2018), regional or long-range transport of pollen from distant sources can also take place (e.g. Smith et al., 2008; Izquierdo et al., 2011; Sikoparija et al., 2013), especially when it comes to small grains, such as birch pollen that can remain suspended in the air for up to a few days (e.g. Siljamo et al., 2008; Veriankaitė et al., 2010) and can therefore be transported through air pathways of 10³ km long (Sofiev et al., 2006). Additionally, other factors, such as altitude (see e.g. Fernández-Rodríguez et al., 2014) and time of year (Pérez-Badía et al., 2011) are known to play an important role on the levels of pollen in the atmosphere.

Considering the aforementioned, forecasts of pollen concentrations cannot only rely on phenological observations and in-situ aerobiological monitoring, as forecasting long-range transport episodes needs to account for both the biological (such as flowering onset, duration and intensity) and the meteorological (such as atmospheric stability, wind parameters, turbulent mixing, dry and wet deposition, chemical and/or physical transformations) mechanisms of pollen release and dispersion in the atmosphere through numerical modelling. However, that would require detailed knowledge of the pollen emission fluxes, to feed the appropriate atmospheric dispersion model (Sofiev et al., 2006), which is not always feasible.

To overcome the shortcomings described above, and keeping in mind that pollen dispersion modelling is not always a straightforward process, a circulation-to-environment (Yarnal, 1994) synoptic climatology method was applied herein, to alternatively elucidate the climatological associations between pollen levels and different air mass types

in a typical Mediterranean environment, such as Thessaloniki, Greece. Thus, a direct link between certain atmospheric patterns and airborne pollen abundance may be established, which could allow the identification of high-risk pollen episodes and the development of more efficient and timely warning systems for allergic citizens but also visitors.

2. Data and methods

2.1. Study area description

The research was conducted in Thessaloniki, the second-largest city in Greece, which is categorized as having a Mediterranean climate with hot and dry summers and mild winters, with the mean temperatures during winter and summer recorded at 7 and 25.3 °C, respectively, and mean annual rainfall at 445 mm.

The city is located to the north of the rather shallow Thermaikos Gulf of the Aegean Sea (40°13'70 N, 22°15'70 E). The mountain of Hortiatís (with height of approximately 1220 m) lies to the east of the area, while several hills are located to the north. To the west, the area is rather flat. The Seich Sou forest is located E-NE of the city and consists mainly of pines, cypresses and evergreen oaks. The forests of Kourí located to the NE and the forests of Mt. Hortiatís located to the SE consist of deciduous forests, mostly oak, hornbeam and hazel. Additionally, plane trees, poplars and cypresses, grow in the surrounding hills, parks and other recreation areas of Thessaloniki. A lot of olive and hazel plantations can be found in the NW and SW prefectures surrounding Thessaloniki. In the city periphery, grasses, amaranths, goosefoots, saltworts, wall pellitories, nettles and mugworts abound (Damialis et al., 2007).

2.2. Pollen data

The pollen data used in this study were collected in the frame of a monitoring program initiated in 1987 by use of a stationary Hirst-type volumetric device, as described in detail by Damialis et al. (2005) and cover the 15-year period 1987–2001. The pollen monitoring site was located on the rooftop of a 7-storey building in the center of the city, at approximately 30 m above ground level. Airborne particles were trapped on an adhesive-coated transparent plastic tape on a 2-hourly scale and this was replaced weekly, chemically processed and analysed with optical microscopy. Finally, all pollen (among other particles) were manually classified and counted and their values were expressed as bi-hourly and daily concentrations of pollen grains per m³ of air. All procedures were conducted following the minimum requirements of the European Aerobiology Society and comprised standardized and worldwide-established aerobiological methods (Galán et al., 2014).

The pollen types selected for this study were those either with the historically highest relative atmospheric abundance in Thessaloniki, or with the highest allergenic capacity (high sensitization rates), or both (Damialis et al., 2019b; Gioulekas et al., 2004). These accounted for a total of 11 taxa, namely *Alnus* spp., *Carpinus* spp., *Chenopodiaceae*, *Corylus* spp., *Cupressaceae*, *Oleaceae*, *Pinaceae*, *Platanus* spp., *Poaceae*, *Quercus* spp. and *Urticaceae*.

2.3. Methodology

In order to link pollen levels recorded in Thessaloniki with atmospheric patterns, the classification software developed by the COST-733 "Harmonization and Applications of Weather Type Classifications for European Regions" (<http://www.cost733.eu>) group was used. This tool uses various established classification techniques and provides several pan-European synoptic grouping schemes. In our study, the 10th Domain of the software (34–49°N and 7–30°E) covering the area of the Balkans, Italy and SE Europe was used and an Optimization Algorithm, namely CKM (a k-means by dissimilar seeds), was selected. In such a non-hierarchical method, the various clusters can be split up, in

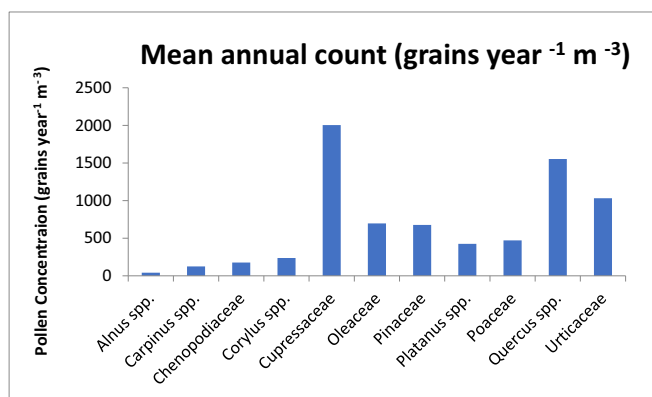


Fig. 1. Mean annual concentration of the 11 most abundant pollen taxa in the air of Thessaloniki for the 15-year period studied, 1987–2001.

order to minimize the within-group variance (Philipp et al., 2010, 2016).

The aforementioned classification technique was used to investigate the possible link between synoptic circulations and elevated pollen concentrations. The variable used to perform the classifications was the mean sea-level pressure fields. For more details on the classification method, the reader can refer to Philipp et al. (2010, 2016). The classification resulted in nine classes, each one with distinct air mass type patterns. Pollen data were then summarized across the various atmospheric patterns.

In the next step, the Performance Index (PI) described in Paschalidou and Kassomenos (2016) and in Paschalidou et al. (2017) was used to check the frequency of elevated pollen concentrations in each class:

$$PI_i = 100 \times \left(\frac{\text{total pollen concentration in } C_i / \text{total pollen concentration}}{\text{Number of days in } C_i / \text{Total number of days}} - 1 \right) \quad (1)$$

Table 1

The number of days with pollen in the air, the total pollen concentration and the PI sign-test per synoptic class and pollen taxon.

Pollen taxa	Pollen season features	C1	C2	C3	C4	C5	C6	C7	C8	C9
Number of days		1162	1056	804	578	493	468	553	282	83
% of days		21.2	19.3	14.7	10.6	9.0	8.5	10.1	5.2	1.5
Alnus spp.	Total count	42.2	46.8	95.6	82.0	60.8	46.5	165.2	64.0	12.1
	PI	−67.6	−60.6	5.9	26.3	9.9	−11.4	166.0	102.0	29.8
Carpinus spp.	Total count	304.9	274.5	250.0	367.8	396.2	60.0	92.3	5.9	121.6
	PI	−23.3	−24.0	−9.1	86.2	135.1	−62.5	−51.2	−93.9	328.5
Chenopodiaceae	Total count	1059.2	807.4	318.0	132.9	169.8	81.5	60.8	1.6	16.6
	PI	88.6	58.2	−18.2	−52.4	−28.7	−64.0	−77.3	−98.9	−58.7
Corylus spp.	Total count	550.1	554.6	657.3	537.7	579.0	130.4	345.7	108.3	94.8
	PI	−27.1	−19.1	25.9	43.3	80.8	−57.1	−3.7	−40.9	75.8
Cupressaceae	Total count	4055.8	3689.7	4567.7	4666.0	5396.0	1020.6	4066.4	1792.2	794.4
	PI	−36.4	−36.39	3.6	47.2	99.6	−60.2	34.1	15.9	74.5
Oleaceae	Total count	2588.9	2818.1	1550.4	1557.6	1243.5	367.1	229.3	5.8	81.5
	PI	16.9	40.0	1.2	41.4	32.4	−58.9	−78.2	−98.9	−48.5
Pinaceae	Total count	1874.8	2161.8	1982.5	1547.7	1687.4	321.8	325.3	17.4	229.3
	PI	−12.9	10.5	33.1	44.6	84.8	−62.9	−68.2	−96.7	49.1
Platanus spp.	Total count	592.4	1226.8	1115.5	1244.9	1358.2	84.9	386.4	22.5	353.7
	PI	−56.3	−0.3	19.1	84.8	136.4	−84.4	−40.1	−93.2	265.7
Poaceae	Total count	2100.6	1897.0	1216.2	731.6	586.0	296.1	171.2	12.0	46.5
	PI	40.4	39.5	17.4	−1.7	−7.7	−50.9	−76.0	−96.7	−56.5
Quercus spp.	Total count	5051.4	4680.5	3882.7	3853.8	4038.7	926.4	345.2	7.3	502.2
	PI	2.3	4.3	13.6	56.9	92.7	−53.4	−85.3	−99.4	42.4
Urticaceae	Total count	2012.3	2970.1	2567.3	2650.4	3833.6	315.0	727.5	21.1	365.7
	PI	−38.6	−0.3	13.1	62.5	175.5	−76.2	−53.4	−97.4	56.1

Total pollen counts are in grains m^{−3}.

The highest PI values (per taxon) are given in bold.

where C_i stands for the different classes ($i = 1, \dots, 9$). Values of PI equal to 0 mean that pollen levels are equally spread among classes, whereas positive/negative PI values denote that the occurrence of high pollen levels is more/less frequent under the atmospheric patterns of the specific class. On the other hand, PI values equal to -100 would mean “pollen-free” classes.

Finally, centroid maps were drawn by the EU-COST-733 software and they were interpreted accordingly, in order to study the synoptic pollen climatology.

3. Results and discussion

3.1. Annual pollen counts

Fig. 1 presents mean annual concentrations of airborne pollen per taxon. The annual concentration (or Annual Pollen Index) is the sum of 365 daily concentrations (pollen grains per cubic meter of air per sampling day). The taxa with the highest pollen concentrations are Cupressaceae, Quercus, Urticaceae, Oleaceae and Pinaceae, in descending order, comprising >80% of the total annual airborne pollen load in Thessaloniki. This is in agreement with other studies in the area (Damialis et al., 2007), thus, highlighting the typical Mediterranean prevalent plant species. It is important to note that among the above most abundant taxa, Cupressaceae (*Cupressus* spp.), Oleaceae (*Olea europaea*) and Urticaceae (*Parietaria* spp.) are at the same time the most allergenic plant families in the Mediterranean (their commonest representatives, in parentheses) (D’Amato et al., 2007). As Damialis et al., 2019b have recently reviewed, the sensitization rates of these pollen taxa may reach up to approximately 15%, 72% and 28%, respectively, of the general atopic population per study area.

Specifically, pollen from *Olea* (olive trees) is considered as one of the most important causes of respiratory allergy in the area (Damialis et al., 2019b; Gioulekas et al., 2004). Similarly, the *Cupressus* genus is widely spread in the Mediterranean region, with cypress trees releasing vast amounts of pollen in the atmosphere and being responsible for high levels of pollinosis (D’Amato et al., 2007). It has been estimated that a typical cypress tree (*C. sempervirens*) or olive tree (*O. europaea*) can produce up to approximately several billions of pollen grains per each individual (Damialis et al., 2011). Likewise, for wall pellitory, which is a

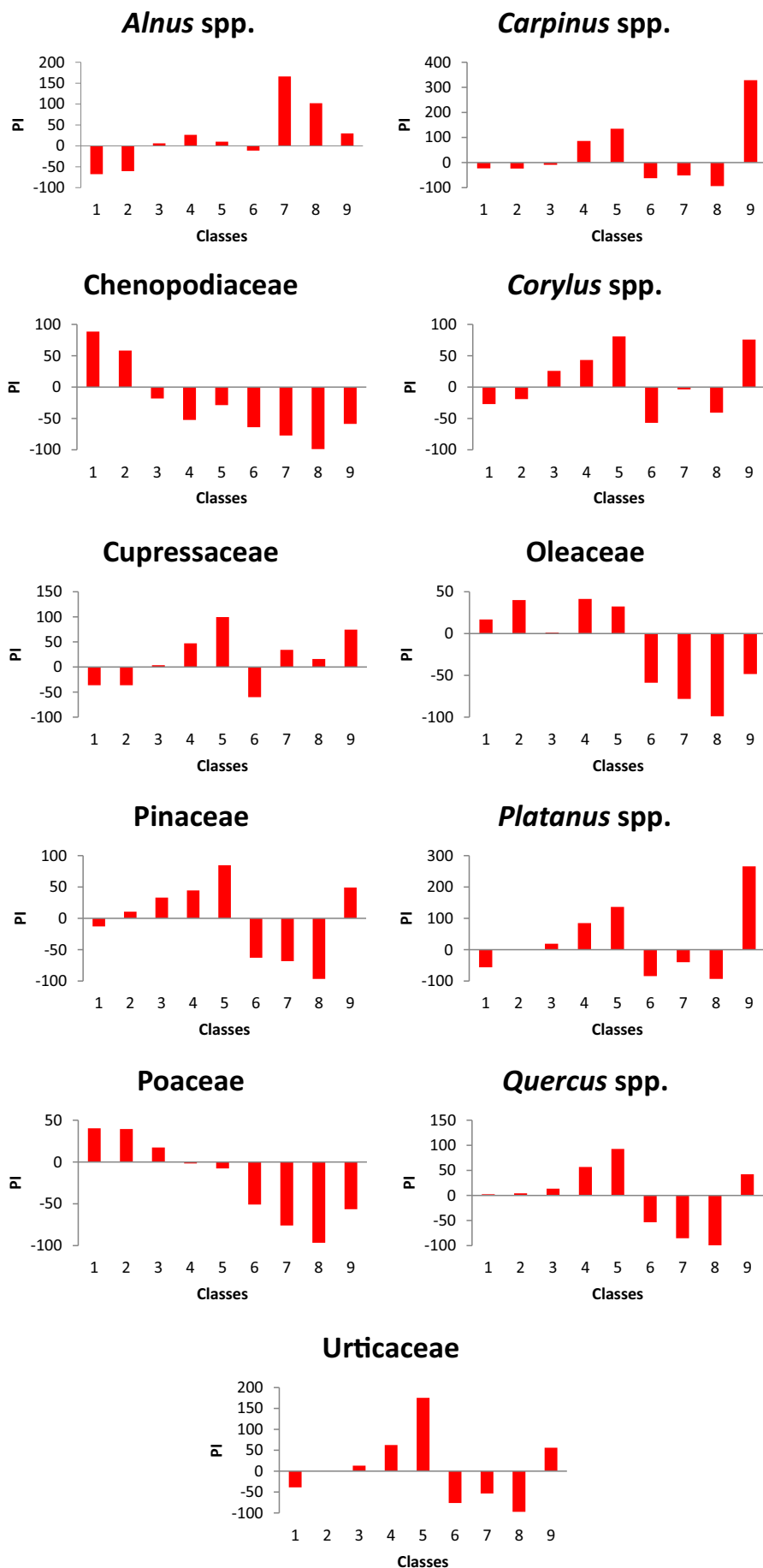


Fig. 2. PI values per class and taxon for the 15-year period studied, 1987–2001.

herbaceous plant growing in patches as multi-stemmed plants, Fotiou et al. (2011) calculated this number to account for up to several billions of pollen grains produced in each m² of plant vegetation. In addition, as wall pellitory is wind-pollinated with very small pollen grains, is favored by pollution and urbanization and has long and more than one flowering seasons per year (Fotiou et al., 2011), it comprises one of the notorious aeroallergens in the Mediterranean basin (D'Amato et al., 2007). However, under the optical microscope, *Parietaria* pollen cannot be distinguished from the *Urtica* one, with has less pronounced allergenicity. Evidently, this may result in overestimations on the allergy risk because of Urticaceae pollen, as the allergenic capacity of the taxon may not be strictly reflected in the monitored atmospheric abundance (Jato et al., 2010). This is also true in Thessaloniki, where *Urtica dioica* L. is common in the metropolitan area (Fotiou et al., 2011).

3.2. Examination of the various classes

Table 1 displays a description of the nine classes produced with the methodology described above. Each class stands for a distinct air mass type. It is apparent that for each taxon there is a number of classes that comprise the days with the highest pollen concentrations. Since long-term health impacts on allergic patients may be related to the actual amount of airborne allergenic pollen in the atmosphere (e.g. Ziello et al., 2012) and higher pollen exposures can lead to higher severity of symptoms (Damialis et al., 2019a), these classes are suggested to reflect the most severe conditions (in terms of elevated pollen levels and presumably allergen potency).

Specifically, C5 appears to be the most severe in five out of the 11 cases studied, namely *Corylus*, Cupressaceae, Pinaceae, *Quercus* and Urticaceae, and the second most severe for *Carpinus* and *Platanus*. Additionally, C1 appears to be the most severe class for Chenopodiaceae and Poaceae (with C2 being the second most severe class for both taxa, and also for Oleaceae). C4 appears to be another important class, as it seems to be the second most severe for two taxa, namely *Quercus* and Urticaceae, and the most severe for Oleaceae. Similarly, C9 appears to be the most severe class for *Carpinus* and *Platanus* and the second most severe for *Corylus*, Cupressaceae and Pinaceae. A totally different

pattern is observed for *Alnus*, where C7 and C8 appear to be the most severe classes.

These results are summarized in Fig. 2, where the PIs are shown per class and taxon. A closer look in Fig. 2 reveals three distinct patterns, i.e. the taxa that group their highest daily pollen concentrations in C5, C4 and C9 (*Carpinus*, *Corylus*, Cupressaceae, Oleaceae, Pinaceae, *Platanus*, *Quercus* and Urticaceae), those with C1 and C2 as their most severe classes (Chenopodiaceae and Poaceae) and finally *Alnus* with C7 and C8 comprising the highest pollen levels. Interestingly, C8 is almost pollen-free for most taxa, with the only exception being *Alnus*.

3.3. Study of the atmospheric patterns

In order to further study the patterns identified above, centroid maps of the surface atmospheric pressure regimes are given in Figs. 3–6.

In the centroid map of C5 (Fig. 3a), a low-pressure system is located over Italy and central Europe, coupled with strong pressure gradient over the western part of the Mediterranean Sea and the Adriatic. The low-pressure system seems to weaken over Greece, where the wind blows from W directions. On the other hand, high pressures are observed over Eastern Europe and Russia. A similar pattern can be observed in the centroid map of C9 (Fig. 3b), though the low-pressure system over Italy is now deeper and the winds over Greece are W-SW. This atmospheric pattern resembles the NW1 depressional weather type, where the low follows a semi-meridional track from NW to SE and is typical of winter (Maheras, 1988). In terms of pollen abundance and seasonality, the synoptic climatology in C5 and C9 reflects “the low winter pollen season” (D'Amato et al., 2007) that coincides with the period December–March and is characterized by heavy loads of pollen from Cupressaceae, Corylaceae, etc.

The aforementioned are confirmed by the heavy loads of *Carpinus*, *Corylus*, Cupressaceae, *Platanus*, Pinaceae, *Quercus* and Urticaceae linked with C5 and C9. Specifically, the *Corylus* trees are known to be the first to release pollen (December to April), followed by Cupressaceae, *Alnus* and *Carpinus*. This early pollen season, coupled with allergenic cross-reactivity, makes hazel a primer of allergic sensitization, so that symptoms can intensify during the birch-pollen season that follows.

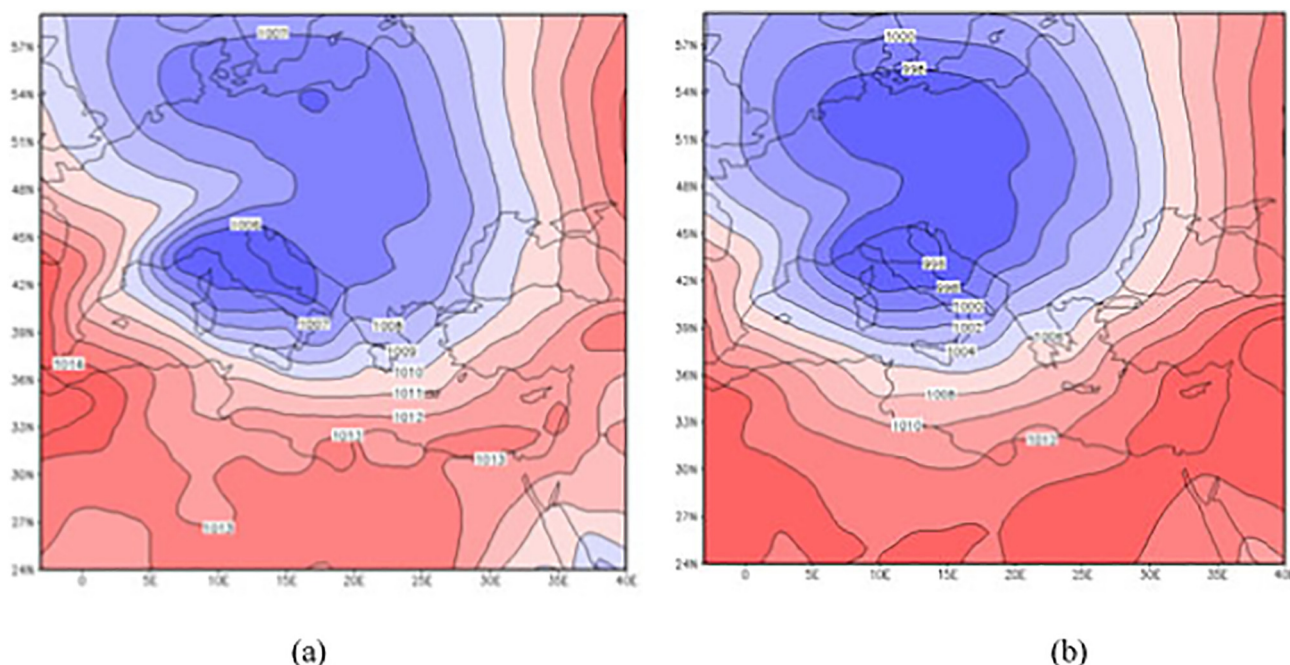


Fig. 3. Surface atmospheric pressure regimes prevailing over the Eastern Mediterranean for C5 and C9.

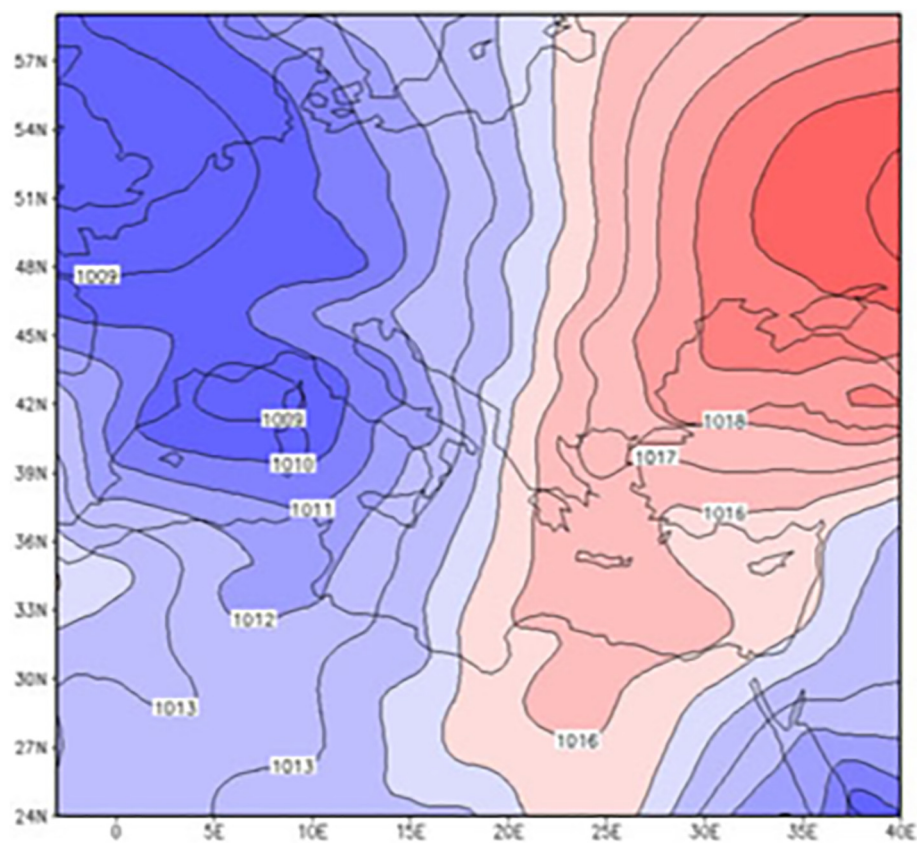


Fig. 4. Surface atmospheric pressure regimes prevailing over the Eastern Mediterranean for C4.

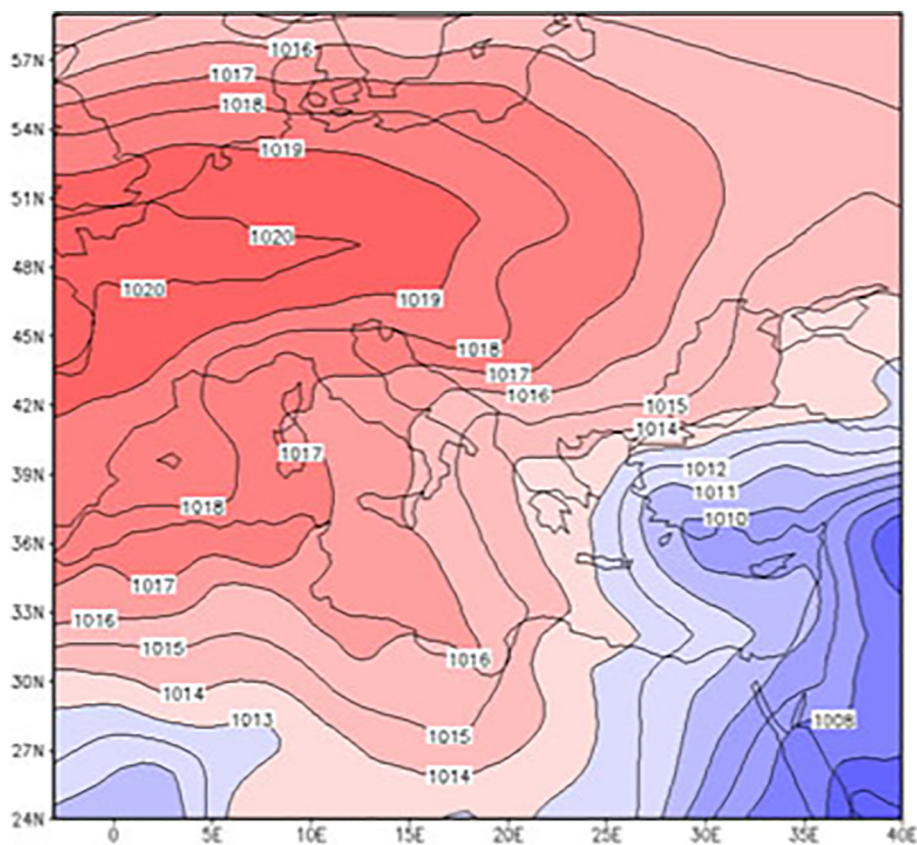


Fig. 5. Surface atmospheric pressure regimes prevailing over the Eastern Mediterranean for C1.

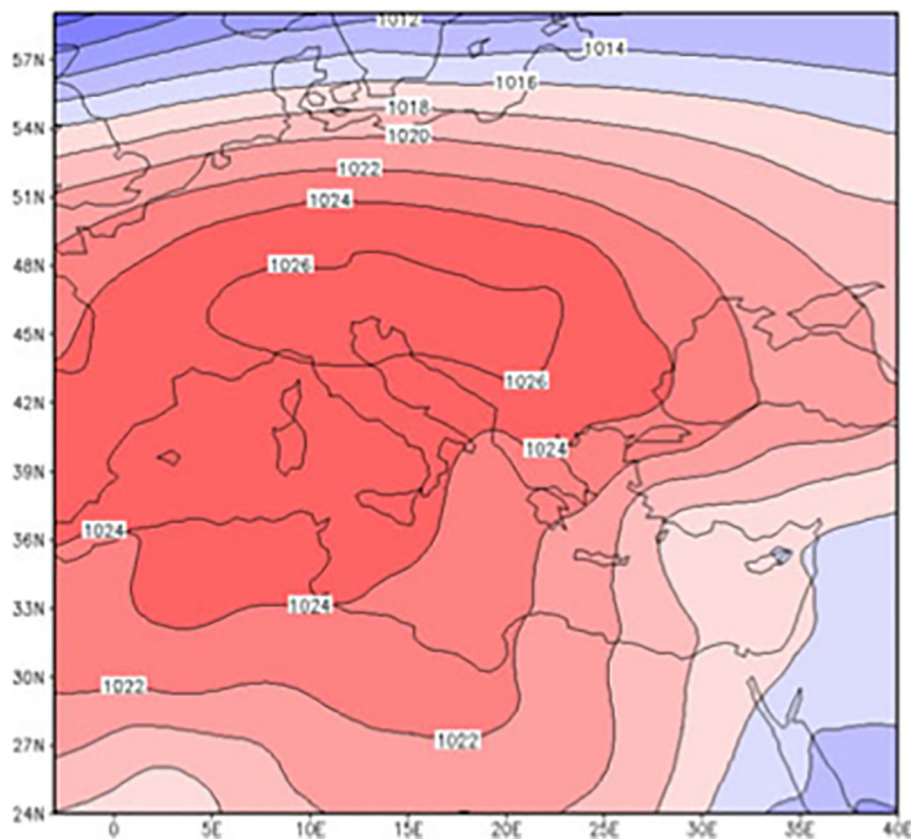


Fig. 6. Surface atmospheric pressure regimes prevailing over the Eastern Mediterranean for C7.

Additionally, medium/long-scale pollen transport cannot be ruled out, as it has been confirmed by aerobiological measurements (Gioulekas et al., 2004) pointing out that, although birch does not exist in the area within a radius of 100 km, its pollen is regularly detected every year. According to Damialis et al. (2005) W winds, as the ones prevailing in C5 and C9, favor the transport of several pollen types, such as of *Corylus* (NW and SW directions).

Regarding Cupressaceae, this family is well-known for winter pollinosis, at a time of the year during which only few other allergenic plants are flowering (Caramiello et al., 1991). However, the cypress pollen season varies highly from year to year and depends on meteorological factors (Hidalgo et al., 2003; Damialis et al., 2005).

The onset of the oak (*Quercus*) season takes place in spring, as well as that of planes, pines and spruces in many parts of Europe (D'Amato et al., 2007). Finally, *Parietaria judaica* (Urticaceae), which is very common in coastal Mediterranean, has two very long flowering periods. The first one takes place at the beginning of spring, often reaching a peak level at the end of April or in May (D'Amato et al., 2007), depending on the climate of the area (Fotiou et al., 2011). A second (shorter) pollen season is observed in late summer. This second pollen season is partially reflected in C4, the second most severe class for Urticaceae (see below).

In the centroid map for C4 (Fig. 4), a combination of high pressures over Eastern Europe and Russia and lower pressures over central Europe can be seen. The winds in Greece blow from N directions. This weather type approximates the SW1 (Maheras, 1988) cyclonic type, where the low follows a semi-meridional pathway from SW to NW, bringing relatively high temperatures, with substantial precipitation in western Greece. It is typical of the intermediate seasons, autumn and spring. In terms of pollen, it reflects the “high spring-summer pollen season” (April–July) (D'Amato et al., 2007) which has high pollen levels of *Parietaria* and *Olea*.

The aforementioned “high spring-summer pollen season” is confirmed by the high levels of pollen from Oleaceae and Urticaceae associated with C4. Specifically, the olive pollen season lasts from April to the end of June and can cause severe symptoms (Gioulekas et al., 2004; Asam et al., 2015). Another interesting aspect is that sensitization to *Olea* pollen allergens are frequently confounded by other allergens (such as from grass) (D'Amato et al., 2007). Once again, medium/long-range transport cannot be ruled out, as according to Damialis et al. (2005), NW winds are known to favor regional or long-distance transport of *Olea* pollen in Thessaloniki.

Regarding Urticaceae, the high levels of pollen linked to C4 probably reflect the second (shorter) pollen season described above. In any case, Makra et al. (2010), who used back-trajectory analysis for the 5-year period 1998–2002, have shown that a fraction of the Urticaceae pollen recorded in Thessaloniki can be linked to air masses arriving from western Europe. On the whole, the long persistence of the *Parietaria* pollen in the atmosphere can result in multi-seasonal symptomatology (Colombo et al., 1998).

In the centroid map of C1 (Fig. 5), an anticyclonic system is located over western Europe. The winds over northern Greece blow from N-NE directions. On the other hand, a cyclonic system is observed over the far Eastern part of the Mediterranean Sea and Cyprus island, which is probably an extension of the SW Asian thermal low. This weather type is typical of mid-late summer in Greece and is linked with the local Etesian winds (Paschalidou and Kassomenos, 2016). In terms of pollen, this weather type reflects the “summer–autumn season” (D'Amato et al., 2007), which lasts from August to October and is characterized by a peak in Poaceae and Chenopodiaceae.

The above are confirmed by the high Poaceae and Chenopodiaceae pollen levels associated with C1. Specifically, the grass flowering period in northern, central and eastern Europe takes place between May and July. However, in the Mediterranean region, the onset and end of the

flowering period takes place one month earlier (D'Amato, 1991). This is also the case in Thessaloniki, as shown by Gioulekas et al. (2004). Nevertheless, the maximum atmospheric levels of grass pollen usually occur 1–2 months after the start of the main flowering season (D'Amato et al., 2007) and coincide with the period marked by the “summer-autumn season” described above. Poaceae pollen is the most important cause of pollinosis throughout Europe, including the Mediterranean region (García-Mozo, 2017). According to epidemiological and clinical studies, sensitization rates to grass pollen can reach up to 80% of the total atopic population (e.g. Erbas et al., 2018).

Similarly, goosefoot (Chenopodiaceae) pollen in Thessaloniki begins its circulation season in May and finishes around September, while the highest pollen levels are observed in August (Gioulekas et al., 2004). According to the same study, 18.3% of the studied population (patients with respiratory allergy) in Thessaloniki presented positive skin allergic reaction to goosefoot, highlighting the importance of the specific aeroallergen in Thessaloniki.

In the centroid map of C7 (Fig. 6), a strong high-pressure system is centered over Italy, giving light NE winds over northern Greece. This atmospheric pattern is often observed over Greece for a few days between mid-December to mid-February, bringing sunny days and fair weather. These time-spells are well-known to the locals as “Alcyone days” and are characterized by light winds or calms. The high levels of *Alnus* (alder) linked to this specific winter-weather pattern do not come as a surprise. Alder is known to be the first, together with hazel, that sheds pollen in early winter months. Although no alder trees exist in Thessaloniki (Damialis et al., 2005), these light winds favor *Alnus* pollen transport from the surrounding regions, in agreement with Damialis et al. (2005) who confirmed the importance of wind persistence in regional pollen transport, particularly under the prevalence of weak winds.

4. Conclusions

This study used a synoptic circulation-to-environment classification method to elucidate the relationship between distinct atmospheric patterns and high pollen levels for 11 taxa in Thessaloniki. The analysis revealed the synoptic climatology of airborne pollen in the area, by means of 4 distinct patterns. Specifically:

- The NW1 depressional weather type, typical of winter in Thessaloniki, and characterized by a low-pressure system located over Italy and central Europe coupled with high pressures over Eastern Europe and Russia, with winds blowing from W or SW directions, is associated with the “low winter pollen season”. Under these atmospheric conditions that take place usually between December–March, high levels of pollen from *Carpinus*, *Corylus*, Cupressaceae, *Platanus*, Pinaceae, *Quercus* and Urticaceae are expected in Thessaloniki.
- The SW1 cyclonic type of weather, typical of the intermediate seasons, autumn and spring, and characterized by high pressures over Eastern Europe and Russia and lower pressures over central Europe, resulting in N winds in Greece, is linked to the “high spring-summer pollen season” (April–July). These atmospheric conditions are linked to high levels of pollen from Oleaceae and Urticaceae in Thessaloniki.
- The weather type characterized by an anticyclonic system located over western Europe and the extension of the SW Asian thermal low, well-known for the mid-late summer Etesian winds blowing from N-NE directions, is associated with the “summer-autumn” pollen season in Thessaloniki. Under these atmospheric conditions, a peak in Poaceae and Chenopodiaceae pollen levels is expected.
- Regional transport of alder pollen is linked to the circulation type characterized by a strong high-pressure system centered over Italy, giving light NE winds over northern Greece that take

place between mid-December to mid-February. Nevertheless, regional/long-range transport of other taxa under the other three atmospheric patterns could not be ruled out.

These findings shed light to the understanding of the climatology of pollen levels in Thessaloniki and highlight that allergy potency can be understood via adopting a synoptic climatology perspective, with special benefits in feeding early-warning systems for known asthmatics and other allergic patients in the area. This way, intervention strategies for alerting the sensitive groups of population and reducing exposure can be more effective. On the other hand, these results could be valuable to local authorities when designing urban green areas, as well as reforestation programs, in order to assess the plants' allergenic potential.

CRediT authorship contribution statement

Anastasia K. Paschalidou: Conceptualization, Methodology, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Kyriaki Psistaki:** Methodology, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Athanasios Charalampopoulos:** Data curation, Writing - review & editing. **Despoina Vokou:** Data curation, Writing - review & editing. **Pavlos Kassomenos:** Conceptualization, Methodology, Visualization, Writing - review & editing. **Athanasios Damialis:** Conceptualization, Data curation, Writing - review & editing.

Declaration of competing interest

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

Acknowledgment

The authors would like to thank the COST 733 group for providing public access to the synoptic catalogues and the software used in this study.

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